Chapter 9

Quality Assurance

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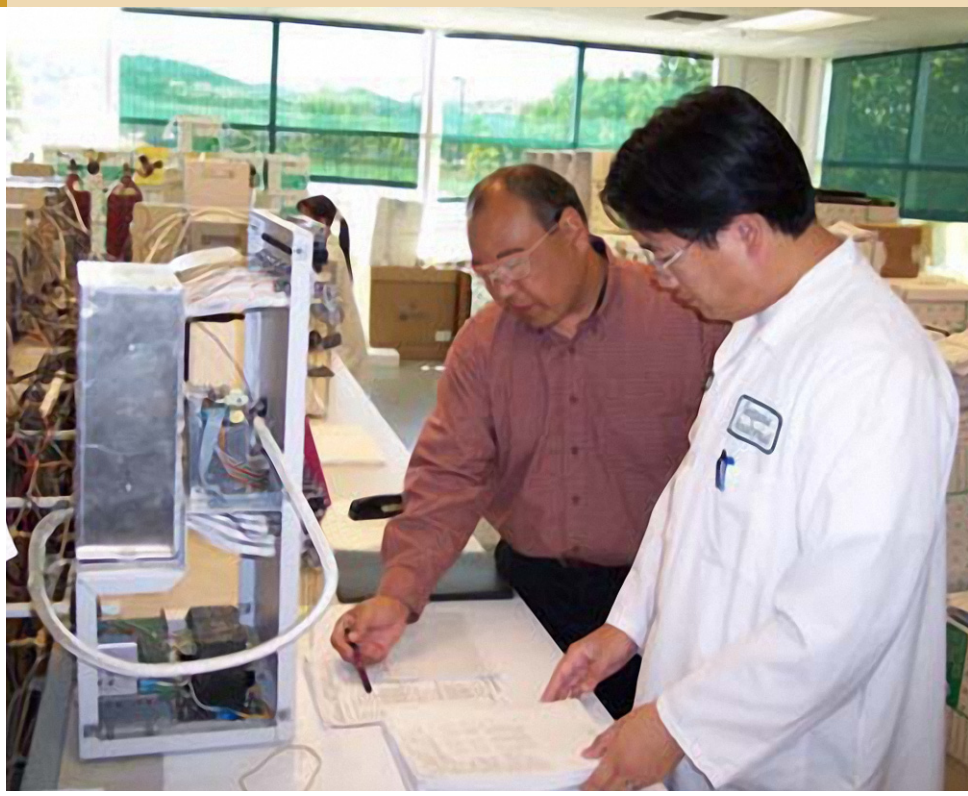

Quality assurance (QA) is a system of activities and processes put in place to ensure that products or services meet or exceed customer specifications. Quality control (QC) consists of activities used to verify that deliverables are of acceptable quality and meet criteria established in the quality planning process.

Lawrence Livermore National Laboratory conducted environmental monitoring activities during 2006 in accordance with the *Environmental Protection Department Quality Assurance Management Plan, Revision 6 (*LLNL 2006a), which is based on the U.S. Department of Energy (DOE) Order 414.1C. This order sets forth policy, requirements, and responsibilities for the establishment and maintenance of plans and actions that ensure quality in DOE programs using a risk-based, graded approach to QA. The process promotes the selective application of QA and management controls based on the risk associated with each activity in order to maximize effectiveness and efficiency in resource use.

LLNL and commercial laboratories analyze environmental monitoring samples using U.S. Environmental Protection Agency (EPA) standard methods when available (see, for example, **Appendix B**). When EPA standard methods are not available, custom analytical procedures, usually developed at LLNL, are used. LLNL uses only State of California-certified

laboratories to analyze its environmental monitoring samples. Commercial laboratories are also required to perform analysis in accordance with DOE's *Quality Systems for Analytical Services* (U.S. DOE 2006h), which is based on quality requirements from the National Environmental Laboratory Accreditation Program and on the ISO 17025 standard. In addition, LLNL requires all analytical laboratories to maintain adequate QA programs and documentation of methods. The radiochemical methods used by LLNL laboratories are described in procedures created and maintained by the laboratory performing the analyses.

9.1 Quality Assurance Activities

Nonconformance reporting and tracking is a formal process used to ensure that problems are identified, resolved, and prevented from recurring. The LLNL Environmental Protection Department (EPD) tracks problems using Nonconformance Reports (NCRs). NCRs are initiated when items or activities are identified that do not comply with procedures or other documents that specify requirements for EPD operations or that cast doubt on the quality of EPD reports, integrity of samples, or data *and* that are not covered by other reporting or tracking mechanisms. Many sampling or data problems are resolved without an NCR being generated.

LLNL averts sampling problems by requiring formal and informal training on sampling procedures. Errors that occur during sampling generally do not result in lost samples but may require extra work on the part of sampling and data management personnel to correct the errors.

LLNL addresses analytical laboratory problems as they arise. Many of the documented problems concern minor documentation errors and are corrected soon after they are identified. Other problems, such as missed holding times, late analytical results, and typographical errors on data reports, account for the remaining issues. These problems are corrected by reissuing reports or correcting paperwork and do not affect associated sample results.

LLNL participates in the DOE Consolidated Auditing Program (DOECAP). Annual, on-site visits to commercial laboratories under contract to LLNL are part of the auditing program to ensure that accurate and defensible data are generated. All commercial laboratories are approved for use as DOE-qualified vendors.

QA staff also track planned environmental monitoring samples that are not collected. The sampling protocol calls for samples to be collected in field containers that may have multiple tests performed on the contents. In turn, each test may produce results with multiple analytes. Sample completeness represents the number of tests performed. **Table 9-1** is a summary of sample completeness.

Table 9-1. Sampling completeness in 2006 for the Livermore site and Site 300.

Medium	Location	Parameter	No. samples planned / No. completed	Percentage completed	Reason for lost samples (no. lost samples)
Air particulate	Livermore site	Radiological	1064 / 1057	99%	Unit off (4); no access (3)
	Livermore site	Beryllium	72 / 72	100%	
	Site 300	Radiological	600 / 580	97%	No access (12); no power (8)
	Site 300	Beryllium	48 / 48	100%	
Air	Livermore site and vicinity	Tritium	448 / 440	98%	No/insufficient flow (8)
	Site 300	Tritium	26 / 26	100%	
Soil and sediment	Livermore site	Radiological	32 / 32	100%	
	Site 300	Radiological	28 / 28	100%	
Arroyo sediment	Livermore site	Radiological	25 / 25	100%	
Vegetation and foodstuffs	Livermore site and vicinity	Radiological	48 / 48	100%	
	Site 300	Radiological	16 / 16	100%	
	Wine (produced in Livermore and France)	Radiological	10 / 10	100%	
Air (TLDs)	Livermore site perimeter	Radiological	56 / 56	100%	
	Livermore Valley	Radiological	88 / 84	95%	Missing (4)
	Site 300	Radiological	52 / 46	88%	Missing (2); no access (4)
Rain	Livermore site	Radiological and chemical	43 / 42	98%	Missing (1)
	Site 300	Radiological and chemical	6 / 6	100%	
Storm water runoff	Livermore site	Radiological and chemical	385 / 385	100%	
	Site 300	Radiological and chemical	230 / 174	76%	No flow at location (56)
Water	Livermore site, Lake Haussmann	Lake level	95 / 95	100%	
		Field measurements	64 / 64	100%	
Wastewater	Livermore site, Building 196	Radiological and metals	950 / 946	99%	Unit malfunction (4)
	Livermore site, C196 (area around Building 196)	Radiological and chemical	283 / 238	100%	
	Livermore site, LWRP effluent	Radiological	48 / 48	100%	
	Livermore site, digester sludge	Radiological and metals	80 / 80	100%	
Sewage ponds wastewater	Site 300, Permit WDR 96-248	Chemical	31 / 30	99.5%	Cancelled (1)
Other surface water	Livermore Valley	Radiological	36 / 36	100%	
Water	Site 300, cooling towers	Chemical	6 / 6	100%	

9.2 Analytical Laboratories and Laboratory Intercomparison Studies

In 2006, LLNL had Blanket Service Agreements (BSAs) with eight commercial analytical laboratories and used two on-site analytical laboratories. All analytical laboratory services used by LLNL are provided by facilities certified by the State of California. LLNL works closely with these analytical laboratories to minimize problems and ensure that QA objectives are maintained.

LLNL uses the results of intercomparison program data to identify and monitor trends in performance and to draw attention to the need to improve laboratory performance. If a laboratory performs unacceptably for a particular test in two consecutive performance evaluation studies, LLNL may select another laboratory to perform the affected analyses until the original laboratory has demonstrated that the problem has been corrected. If an off-site laboratory continues to perform unacceptably or fails to prepare and implement acceptable corrective action responses, the LLNL Procurement Department formally notifies the laboratory of its unsatisfactory performance. If the problem persists, the off-site laboratory's BSA could be terminated. If an on-site laboratory continues to perform unacceptably, use of that laboratory could be suspended until the problem is corrected.

In 2006, two LLNL laboratories participated in the DOE-sponsored Mixed Analyte Performance Evaluation Program (MAPEP). The participating laboratories were the Environmental Monitoring Radiological Laboratory (EMRL) and the Hazards Control Department's Analytical Laboratory (HCAL).

For EMRL, 54 of the 55 reported results were determined to be acceptable, one was acceptable with warning, and none were unacceptable (based on MAPEP-established control limits). See **Table 9-2**. For HCAL, four out of the five results fell within the acceptance control limits and one result fell within the warning limit. See **Table 9-3**.

HCAL also participated in two Environmental Resource Associates (ERA) performance evaluation studies in 2006. See **Table 9-4**. Fourteen of the 15 analytes fell within acceptable limits with one analyte (aluminum) falling outside the acceptable range (Study WP-121). A subsequent aluminum sample was analyzed (Study WP-138), and the reported value was 1030 micrograms per liter (μg/L) for an assigned value of 975, well within the 2σ control limit established by ERA for EPA Method 200.7.

Although laboratories with BSAs are also required to participate in laboratory intercomparison programs, permission to publish their results for comparison purposes was not granted for 2006. To obtain MAPEP reports that include the results from all participating laboratories, see http://www.inl.gov/resl/mapep/reports.html.

Table 9-2. EMRL performance in the MAPEP Intercomparison Program Studies for 2006.

Medium	Study	Analyte	Result	Reference value	Flag[a]	Acceptance range[b]	Uncertainty value
Air filter (Bq/sample)	MAPEP-06-GrF15	Gross alpha	0.210	0.361	A	>0.000 – 0.722	0.00118
		Gross beta	0.382	0.8481	A	0.241 – 0.722	0.00213
	MAPER-06-RdF15	Uranium-238	1.52	1.69	A	(c)	0.00358
		Cesium-134	2.66	2.934	A	2.054 – 3.814	0.165
		Cesium-137	2.43	2.531	A	1.772 – 3.290	0.196
		Cobalt-57	4.21	4.096	A	2.867 – 5.325	0.242
		Cobalt-60	2.19	2.186	A	1.530 – 2.842	0.183
		Plutonium-238	0.0740	0.067	A	0.047-0.087	0.0129
		Plutonium-239/240	0.000427	0.00041	A	(c)	0.000379
		Zinc-65	3.46	3.423	A	3.03 – 5.63	0.790
	MAPEP-06-GrF16	Gross alpha	0.0619	0.290	A	>0.0 – 0.580	0.00341
		Gross beta	0.268	0.359	A	0.180 – 0.538	0.00853
	MAPEP-06-RdF16	Cesium-134	2.75	3.147	A	2.20 – 4.09	0.170
		Cesium-137	1.74	1.805	A	1.26 – 2.35	0.263
		Cobalt-57	2.78	2.582	A	1.81 – 3.36	0.275
		Cobalt-60	1.58	1.577	A	1.10 – 2.05	0.184
		Manganese-54	1.97	1.92	A	1.34 – 2.50	0.311
		Plutonium-238	0.138	0.118	A	0.08 – 0.15	0.0239
		Plutonium-239/240	6.63×10^{-4}	None	A	(c)	5.20×10^{-4}
Aqueous (Bq/L)	MAPEP-06-MaW15	Cesium-134	88.7	95.10	A	66.57 – 123.63	7.15
		Cobalt-57	170	166.12	A	116.28 – 215.96	11.6
		Cobalt-60	148	153.50	A	107.45 – 199.55	7.86
		Hydrogen-3	923	952.01	A	666.41 – 1237.61	12.0
		Manganese-54	317	315.00	A	220.50 – 409.50	24.4
		Plutonium-238	0.957	0.91	A	0.64 – 1.18	0.164
		Plutonium-239/240	0.00296	0.0071	A	(c)	0.00282
		Zinc-65	229	228.16	A	159.71 – 296.61	16.6
	MAPEP-06-GrW15	Gross alpha	0.241	0.581	A	>0.0 – 1.162	0.00608
		Gross beta	1.09	1.13	A	0.56 – 1.70	0.0213
	MAPEP-06-MaW16	Cesium-134	105	112.82	A	78.97 – 146.66	5.22
		Cesium-137	195	196.14	A	137.30 – 254.98	15.0
		Cobalt-57	238	213.08	A	149.16 – 277.00	26.9
		Cobalt-60	46.5	47.5	A	33.2 – 61.8	3.44
		Hydrogen-3	442	428.85	A	300.20 – 557.50	13.2
		Plutonium-238	1.33	1.39	A	0.97 – 1.81	0.226
		Plutonium-239/240	1.84	1.94	A	1.36 – 2.52	0.308

Table 9-2 (cont.). EMRL performance in the MAPEP Intercomparison Program Studies for 2006.

Medium	Study	Analyte	Result	Reference value	Flag[a]	Acceptance range[b]	Uncertainty value
		Zinc-65	189	176.37	A	123.46 – 229.28	38.5
	MAPEP-06-GrW16	Gross alpha	0.878	1.033	A	>0.0 – 2.066	0.0225
		Gross beta	1.06	1.03	A	0.52 – 1.54	0.0477
Soil (Bq/kg)	MAPEP-06-MaS15	Cesium-137	343	339.69	A	237.78 – 441.60	29.5
		Cobalt-57	643	656.29	A	459.40 – 853.18	37.0
		Cobalt-57	643	656.29	A	459.40 – 853.18	37.0
		Manganese-54	340	346.77	A	242.74 – 450.80	25.8
		Plutonium-238	62.1	61.15	A	42.80 – 79.50	10.2
		Potassium-40	585	604	A	423 – 785	88.3
		Zinc-65	663	657.36	A	460.15 – 854.57	52
	MAPEP-06-MaS16	Cesium-134	403	452.13	A	316.49 – 587.77	22.2
		Cesium-137	505	525.73	A	368.01 – 683.45	33.8
		Cobalt-57	721	676.33	A	473.43 – 879.23	60.3
		Manganese-54	593	594.25	A	415.98 – 772.52	61.7
		Plutonium-238	82.6	82	A	57 – 107	13.6
		Plutonium-239/240	0.331	0.93	A	(c)	0.193
		Potassium-40	584	604	A	423 – 785	80.5
		Zinc-65	956	903.61	A	632.53 – 1174.69	158

(a) Gross alpha flags:

A = Result acceptable. Bias ≤ ±100% with a statistically positive result at two standard deviations.

N = Result not acceptable. Bias > ±100% or the reported result is not statistically positive at two standard deviations.

Gross beta flags:

A = Result acceptable. Bias ≤ ±50% with a statistically positive result at two standard deviations.

N = Result not acceptable. Bias > ±50% or the reported result is not statistically positive at two standard deviations.

All other flags:

A = Result acceptable. Bias ≤20%.

W = Result acceptable with warning. Bias >20% and bias ≤30%.

N = Result not acceptable. Bias >30%.

(b) Significant figures shown are those of the MAPEP.

(c) Acceptance range not provided for this analysis.

Table 9-3. HCAL performance in the MAPEP Intercomparison Program Studies for 2006.

Medium	Study	Analyte	Result	Reference value	Flag[a]	Acceptance range	Uncertainty value
Air filter (Bq/sample)	MAPEP-06-GrF16	Gross alpha	0.125	0.290	A	>0.0 – 0.580	0.021
		Gross beta	0.49	0.359	A	0.180 – 0.538	0.04
Aqueous (Bq/L)	MAPEP-06-GrW16	Gross alpha	1.11	1.033	A	>0.0 – 2.066	0.134
		Gross beta	1.95	1.03	N	0.52 – 1.54	0.13
	MAPEP-06-MaW16	Hydrogen-3	543	428.85	W	300.20 – 557.50	29

(a) Gross alpha flags:

A = Result acceptable. Bias ≤ ±100% with a statistically positive result at two standard deviations.

N = Result not acceptable. Bias > ±100% or the reported result is not statistically positive at two standard deviations.

Gross beta flags:

A = Result acceptable. Bias ≤ ±50% with a statistically positive result at two standard deviations.

N = Result not acceptable. Bias > ±50% or the reported result is not statistically positive at two standard deviations.

All other flags:

A = Result acceptable. Bias ≤20%.

W = Result acceptable with warning. Bias >20% and bias ≤30%.

N = Result not acceptable. Bias >30%.

Table 9-4. HCAL performance in the ERA Intercomparison Program Studies for 2006.

Type of analysis	Study	Analyte	Reported value	ERA assigned value	Control limits	Warning limits	Performance evaluation
Radiological (pCi/L)	RAD-66	Gross alpha	11.8	9.96	1.30 – 18.6	4.19 – 15.7	Acceptable
		Gross beta	8.27	8.85	0.190 – 17.5	3.08 – 14.6	Acceptable
		Tritium	3800	4050	3350 – 4750	3580 – 4520	Acceptable
Nonradiological (µg/L)	WP-121	Aluminum	427	300	219 – 385	246 – 357	Not acceptable
		Arsenic	832	837	704 – 978	750 – 933	Acceptable
		Beryllium	693	726	618 – 820	652 – 786	Acceptable
		Cadmium	568	581	496 – 660	523 – 632	Acceptable
		Chromium	689	663	578 – 750	606 – 721	Acceptable
		Copper	690	703	633 – 773	661 – 749	Acceptable
		Iron	853	849	749 – 960	785 – 925	Acceptable
		Lead	730	760	665 – 852	696 – 821	Acceptable
		Mercury	27	26.4	16.2 – 35.6	19.5 – 32.3	Acceptable
		Nickel	973	962	866 – 1070	904 – 1040	Acceptable
		Silver	105	106	90.4 – 122	95.6 – 116	Acceptable
		Zinc	1160	1120	963 – 1280	1020 – 1230	Acceptable

9.3 Duplicate Analyses

Duplicate (collocated) samples are distinct samples of the same matrix collected as close to the same point in space and time as possible. Collocated samples that are processed and analyzed by the same laboratory provide intralaboratory information about the precision of the entire measurement system, including sample acquisition, homogeneity, handling, shipping, storage, preparation, and analysis. Collocated samples that are processed and analyzed by different laboratories provide interlaboratory information about the precision of the entire measurement system (U.S. EPA 1987). Collocated samples may also be used to identify errors such as mislabeled samples or data entry errors.

Tables 9-5, **9-6**, and **9-7** present statistical data for collocated sample pairs, grouped by sample matrix and analyte. Samples from both the Livermore site and Site 300 are included. **Tables 9-5** and **9-6** are based on data pairs in which both values are detections (see **Section 9.4**). **Table 9-7** is based on data pairs in which either or both values are nondetections.

When there were more than eight data pairs with both results in each pair considered detections, precision and regression analyses were performed; those results are presented in **Table 9-5**. When there were eight or fewer data pairs with both results above the detection limit, the ratios of the individual duplicate sample pairs were averaged; the mean, minimum, and maximum ratios for selected analytes are given in **Table 9-6**. The mean ratio should be between 0.7 and 1.3. When either of the results in a pair is a nondetection, the other result should be a nondetection or less than two times the detection limit. **Table 9-7** identifies the sample media and analytes for which at least one pair failed this criterion. Media and analytes with fewer than four pairs are omitted from the table.

Precision is measured by the percent relative standard deviation (%RSD); see the EPA's *Data Quality Objectives for Remedial Response Activities: Development Process*, Section 4.6 (U.S. EPA 1987). Acceptable values for %RSD vary greatly with matrix, analyte, and analytical method; however, lower values represent better precision. The results for %RSD given in **Table 9-5** are the 75th percentile of the individual precision values. Routine and collocated sample results show good %RSD—90% of the pairs have %RSD of 39% or better; 75% have %RSD of 19% or better.

Regression analysis consists of fitting a straight line to the collocated sample pairs. Good agreement is indicated when the data lie close to a line with a slope equal to 1 and an intercept equal to 0, as illustrated in **Figure 9-1**. Allowing for normal analytical variation, the slope of the fitted line should be between 0.7 and 1.3, and the absolute value of the intercept should be less than the detection limit. The coefficient of determination (r^2) should be greater than 0.8. These criteria apply to pairs in which both results are above the detection limit.

Collocated sample comparisons are more variable when the members of the pair are analyzed by different methods or with different criteria for analytical precision. For example, radiological analyses using different counting times or different laboratory aliquot sizes will

Table 9-5. Quality assurance collocated sampling: Summary statistics for analytes with more than eight pairs in which both results were above the detection limit.

Medium	Analyte	N[a]	%RSD[b]	Slope	r^2[c]	Intercept
Air	Gross alpha[d]	37	70.7%	0.261	0.07	1.48×10^{-5} (Bq/m^3)
	Gross beta	95	20.4%	0.847	0.88	3.19×10^{-5} (Bq/m^3)
	Beryllium	12	7.39%	1.03	0.96	0.0839 (pg/m^3)
	Uranium-235[e]	12	18.5%	1.13	0.1	1.09×10^{-5} (µg/m^3)
	Uranium-238[e]	12	23.8%	0.561	0.08	5.69×10^{-5} (µg/m^3)
	Uranium-235/ uranium-238 (ratio)[d]	12	4.89%	0.772	0.69	0.000971 (ratio)
	Tritium[e]	24	30.5%	0.59	0.98	0.11 (Bq/m^3)
Dose (TLD)	90-day radiological dose	30	3.61%	0.983	0.84	0.345 (mrem)
Groundwater	Gross beta[d]	43	18.6%	0.963	0.75	0.019 (Bq/L)
	Arsenic	24	7.62%	1	1	–0.000188 (mg/L)
	Barium	21	3.63%	1	0.96	0.00217 (mg/L)
	Nitrate (as NO_3)	19	2.53%	1	1	–0.187 (mg/L)
	Potassium[e]	22	43.5%	0.788	0.29	6.04 (mg/L)
	Tritium	11	6.42%	0.978	1	2.98 (Bq/L)
	Uranium-234+ uranium-233[e]	16	7.89%	0.555	0.53	0.0332 (Bq/L)
	Uranium-235[e]	15	27.7%	0.479	0.34	0.00195 (Bq/L)
	Uranium-238[e]	16	6.07%	0.557	0.48	0.0244 (Bq/L)
	Vanadium	12	2.92%	1.02	1	–0.00186 (mg/L)
Sewer	Gross beta[d]	52	15.7%	0.826	0.5	0.000127 (Bq/mL)
	Tritium	15	2.9%	1.02	1	–0.00344 (Bq/mL)

(a) Number of collocated pairs included in regression analysis.

(b) 75th percentile of percent relative standard deviations (%RSD) where %RSD = $\left(\frac{200}{\sqrt{2}}\right)\frac{|x_1 - x_2|}{x_1 + x_2}$ and x_1 and x_2 are the reported concentrations of each routine–duplicate pair.

(c) Coefficient of determination.

(d) Outside acceptable range of slope or r^2 because of variability.

(e) Outside acceptable range of slope or r^2 because of outliers.

have different amounts of variability. Different criteria are rarely, if ever, used with collocated sample pairs in LLNL environmental monitoring sampling. Different criteria are sometimes used in special studies when more than one regulatory agency is involved.

Data sets that do not meet LLNL regression analysis criteria fall into one of two categories—outliers and high variability. Outliers can occur because of data transcription errors, measurement errors, or real but anomalous results. Of the 20 data sets reported in **Table 9-5**, seven did not meet the criterion for acceptability because of outliers. **Figure 9-2** illustrates a set of collocated pairs with one outlier.

Table 9-6. Quality assurance collocated sampling: Summary statistics for selected analytes with eight or fewer pairs in which both results were above the detection limit.

Media	Analyte	N[(a)]	Mean ratio	Minimum ratio	Maximum ratio
Drinking water	Gross beta	1	1.2	1.2	1.2
Groundwater	Gross alpha	4	1.2	0.96	1.2
	Radium 226	2	1.1	0.92	1.2
Runoff (from rain)	Gross alpha	2	1.2	1	1.3
	Gross beta	5	1.3	0.52	2.8
	Uranium-233+234	2	0.86	0.82	0.9
	Uranium-235+236	1	0.68	0.68	0.68
	Uranium-238	2	0.95	0.82	1.1
	Uranium-238 by mass measurement	1	0.79	0.79	0.79
Soil	Gross alpha	1	0.93	0.93	0.93
	Gross beta	1	1	1	1
	Cesium-137	3	0.9	0.62	1.1
	Tritium	1	4.8	4.8	4.8
	Tritium	1	3.1	3.1	3.1
	Potassium-40	4	0.97	0.94	1
	Plutonium-238	2	0.91	0.69	1.1
	Plutonium-239+240	3	0.88	0.73	1
	Radium-226	4	0.97	0.93	1
	Radium-228	4	0.96	0.92	1
	Thorium-228	4	0.94	0.86	0.99
	Uranium-235	4	0.95	0.74	1.1
	Uranium-238	4	0.94	0.78	1.1
Vegetation	Tritium	6	1.9	0.71	5.9

(a) Number of collocated pairs used in ratio calculations.

Table 9-7. Quality assurance collocated sampling. Summary statistics for analytes with at least four pairs in which one or both results were below the detection limit.

Medium	Analyte	No. inconsistent pairs[(a)]	No. pairs
Groundwater	Arsenic	1	18
Groundwater	Tritium	1	27
Sewer	Toluene	1	5
Sewer	Tritium	1	37

(a) Inconsistent pairs are those for which one of the results is more than twice the reporting limit of the other.

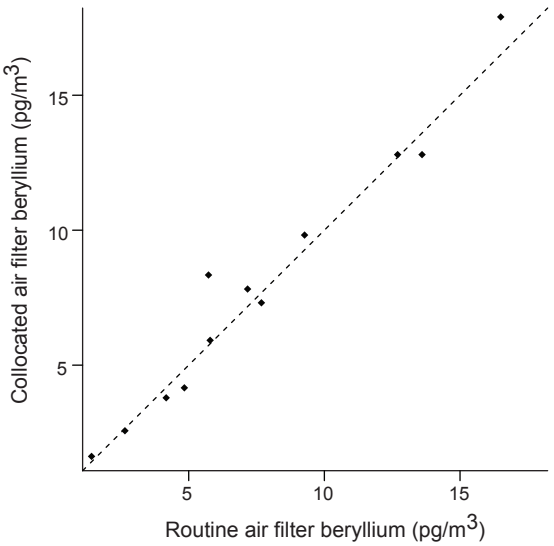

Figure 9-1. Example of data points that demonstrate good agreement between collocated sample results using beryllium concentrations in air.

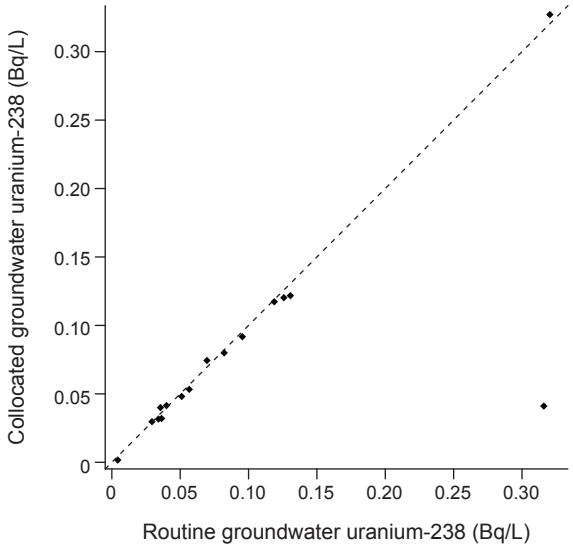

Figure 9-2. Example of data with an outlier using collocated groundwater uranium-238 concentrations.

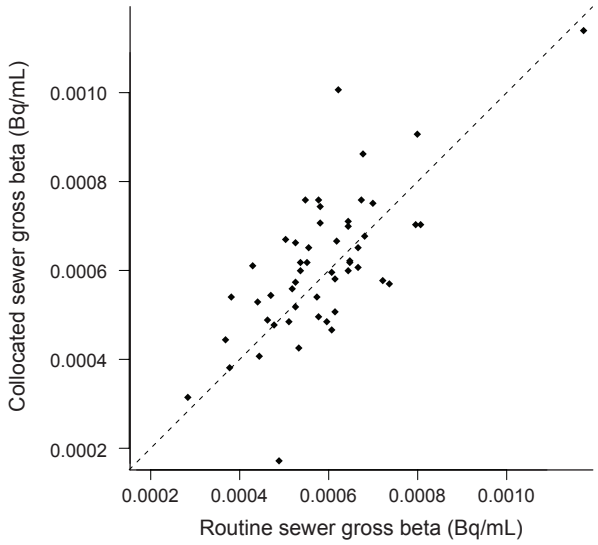

Figure 9-3. Example of variability using sewer gross beta concentrations from collocated samples.

The second category, high variability, tends to occur at extremely low concentrations (see **Figure 9-3** for an example). Low concentrations of radionuclides on particulates in air highlight this effect because a small number of radionuclide-containing particles on an air filter can significantly affect results. Other causes of high variability are sampling and analytical methodology. Analyses of total organic carbon and total organic halides in water are particularly difficult to control. Of the 20 data sets listed in **Table 9-5**, four show sufficient variability in the results to make them fall outside the acceptable range.

9.4 Data Presentation

The data tables in **Appendix B** were created using computer scripts that retrieve data from a database, convert the data into Système International (SI) units when necessary, calculate summary statistics, format data as appropriate, format the table into rows and columns, and present a draft table. The tables are reviewed by the responsible analyst. Analytical laboratory data and the values calculated from the data are normally displayed with two, or at most, three significant digits. Significant trailing zeros may be omitted.

9.4.1 Radiological Data

Most of the data tables in **Appendix B** display radiological data as a result plus or minus (±) an associated 2σ uncertainty. This measure of uncertainty represents intrinsic variation in the measurement process, most of which is due to the random nature of radioactive decay (see **Section 9.6**). The uncertainties are not used in summary statistic calculations. Any radiological result exhibiting a 2σ uncertainty greater than or equal to 100% of the result is considered a nondetection.

Some radiological results are derived from the number of sample counts minus the number of background counts inside the measurement apparatus. Therefore, a sample with a concentration at or near background may have a negative value. Such results are reported in the data tables and used in the calculation of summary statistics and statistical comparisons.

Some data tables provide a limit-of-sensitivity value instead of an uncertainty when the radiological result is below the detection criterion. Such results are displayed with the limit-of-sensitivity value in parentheses.

9.4.2 Nonradiological Data

Nonradiological data reported by the analytical laboratory as being below the reporting limit are displayed in tables with a less-than symbol (<). Reporting limit values are used in the calculation of summary statistics, as explained below.

9.5 Statistical Comparisons and Summary Statistics

Standard comparison techniques such as regression analysis, *t*-tests, and analysis of variance have been used where appropriate to determine the statistical significance of trends or differences between means. When a comparison is made, the results are described as either "statistically significant" or "not statistically significant." Other uses of the word "significant" in this report do not imply that statistical tests have been performed but relate to the concept of practical significance and are based on professional judgment.

Summary statistics are calculated according to Woods (2005). The usual summary statistics are the median, which is a measure of central tendency, and interquartile range (IQR), which is a measure of dispersion (variability). However, some data tables may present other measures at the discretion of the analyst.

The median indicates the middle of the data set (i.e., half of the measured results are above the median, and half are below). The IQR is the range that encompasses the middle 50% of the data set. The IQR is calculated by subtracting the 25th percentile of the data set from the 75th percentile of the data set. When necessary, the percentiles are interpolated from the data. Different software vendors may use slightly different formulas for calculating percentiles. Radiological data sets that include values less than zero may have an IQR greater than the median. To calculate the median, at least four values are required; to calculate the IQR at least six values are required.

Summary statistics are calculated from values that, if necessary, have already been rounded, such as when units have been converted from picocuries (pCi) to becquerels (Bq), and are then rounded to an appropriate number of significant digits. The calculation of summary statistics is also affected by the presence of nondetections. A nondetection indicates that no specific measured value is available; instead, the best information available is that the actual value is less than the reporting limit. Adjustments to the calculation of the median and IQR for data sets that include nondetections are described below.

For data sets with all measurements above the reporting limit and radiological data sets that include reported values below the reporting limit, all reported values, including any below the reporting limit, are included in the calculation of summary statistics.

For data sets that include one or more values reported as "less than the reporting limit," the reporting limit is used as an upper bound value in the calculation of summary statistics.

If the number of values is odd, the middle value (when sorted from smallest to largest) is the median. If the middle value and all larger values are detections, the middle value is reported as the median. Otherwise, the median is assigned a less-than (<) sign.

If the number of values is even, the median is halfway between the middle two values (i.e., the middle two when the values are sorted from smallest to largest). If both of the middle two values and all larger values are detections, the median is reported. Otherwise, the median is assigned a less-than (<) sign.

If any value used to calculate the 25th percentile is a nondetection, or any value larger than the 25th percentile is a nondetection, the IQR cannot be calculated and is not reported.

The median and the IQR are not calculated for data sets with no detections.

9.6 Reporting Uncertainty in Data Tables

The measurement uncertainties associated with results from analytical laboratories are represented in two ways. The first of these, significant digits, relates to the resolution of the

measuring device. For example, if an ordinary household ruler with a metric scale is used to measure the length of an object in centimeters (cm), and the ruler has tick marks every one-tenth of a centimeter, the length can reliably and consistently be measured to the nearest tenth of a centimeter (i.e., to the nearest tick mark). An attempt to be more precise is not likely to yield reliable or reproducible results because it would require a visual estimate of a distance between tick marks. The appropriate way to report a measurement using this ruler would be, for example, 2.1 cm, which would indicate that the "true" length of the object is nearer to 2.1 cm than to 2.0 cm or 2.2 cm (i.e., between 2.05 and 2.15 cm). A measurement of 2.1 cm has two significant digits. Although not stated, the uncertainty is considered to be ± 0.05 cm. A more precise measuring device might be able to measure an object to the nearest one-hundredth of a centimeter; in that case a value such as "2.12 cm" might be reported. This value would have three significant digits and the implied uncertainty would be ± 0.005 cm. A result reported as "3.0 cm" has two significant digits. That is, the trailing zero is significant and implies that the true length is between 2.95 and 3.05 cm—closer to 3.0 than to 2.9 or 3.1 cm.

When performing calculations with measured values that have significant digits, all digits are used. The number of significant digits in the calculated result is the same as that of the measured value with the fewest number of significant digits.

Most unit conversion factors do not have significant digits. For example, the conversion from milligrams to micrograms requires multiplying by the fixed (constant) value of 1000. The value 1000 is exact; it has no uncertainty and therefore the concept of significant digits does not apply.

The other method of representing uncertainty is based on random variation. For radiological measurements, there is variation due to the random nature of radioactive decay. As a sample is measured, the number of radioactive decay events is counted and the reported result is calculated from the number of decay events that were observed. If the sample is recounted, the number of decay events will almost always be different because radioactive decay events occur randomly. Uncertainties of this type are reported in this volume as 2σ uncertainties. A 2σ uncertainty represents the range of results expected to occur approximately 95% of the time if a sample were to be recounted many times. A radiological result reported as, for example, "2.6 ± 1.2 Bq/gram (g)," would indicate that with approximately 95% confidence, the "true" value is in the range of 1.4 to 3.8 Bq/g (i.e., 2.6 – 1.2 = 1.4 and 2.6 + 1.2 = 3.8).

The concept of significant digits applies to both the radiological result and its uncertainty. So, for example, in a result reported as "2.6 ± 1.2," both the measurement and its uncertainty have the same number of significant digits, that is, two. When expanding an interval reported in the "±" form, for example "2.4 ± 0.44," to a range of values, the rule described above for calculations involving significant digits must be followed. For example, 2.4 – 0.44 = 1.96. However, the measurements 2.4 and 0.44 each have two significant digits, so 1.96 must be rounded to two significant digits, i.e., to 2.0. Similarly, 2.4 + 0.44 = 2.84, and this must be

rounded to 2.8. Therefore, a measurement reported as "2.4 ± 0.44 Bq/g" would represent an interval of 2.0 to 2.8 Bq/g.

When rounding a value with a final digit of "5," the software that was used to prepare the data tables follows the Institute of Electrical and Electronics Engineers Standard 754-1985, which is "go to the even digit." For example, 2.45 would be rounded down to 2.4, and 2.55 would be rounded up to 2.6.

9.7 Quality Assurance Process for the Environmental Report

Unlike the preceding sections, which focused on standards of accuracy and precision in data acquisition and reporting, this section describes the actions that are taken to ensure the accuracy of this data-rich environmental report, the preparation of which involves many operations and many people. The key elements that are used to ensure accuracy are described below.

Analytical laboratories send reports electronically, which are loaded directly into the database. This practice should result in perfect agreement between the database and data in printed reports from the laboratories. In practice, however, laboratory reporting is not perfect, so the Data Management Team (DMT) carefully checks all incoming data throughout the year to make sure that electronic and printed reports from the laboratories agree. While not formally part of the QA process for the preparation of this environmental report, this aspect of QC is essential to the report's accuracy. Because of this ongoing QC of incoming data, data stored in the database and used to prepare the annual environmental report tables are unlikely to contain errors.

As described in **Section 9.4**, scripts are used to pull data from the database directly into the format of the table, including unit conversion and summary statistic calculations. All of the data tables contained in **Appendix B** were prepared for this report in this manner. For these tables, it is the responsibility of the appropriate analyst to check each year that the table is up-to-date (e.g., new locations/analytes added, old ones removed), that the data agree with the data he or she has received from DMT, and that the summary calculations have been done correctly.

For this 2006 environmental report, LLNL staff checked tables and figures in the body of the report as described above. Forms to aid in the QC of tables and figures were distributed along with the appropriate figure, table, and text, and a coordinator kept track of the process. Items that were checked included figure captions and table titles for clarity and accuracy, data accuracy and completeness, figure labels and table headings, units, significant digits, and consistency with text. Completed QC forms and the corrected figures or tables were returned to the report editors, who, in collaboration with the responsible author, ensured that corrections were made.

9.8 Errata

Appendix G contains the protocol for errata in LLNL *Environmental Reports* and the errata for LLNL *Environmental Report 2004* and *Environmental Report 2005*.