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Final Report on Jobin Yvon Contained Inductively Coupled Plasma Emission Spectrometer (ICP-ES)

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1.0 Summary

A new Inductively Coupled Plasma - Emission Spectrometer (ICP-ES) was recently purchased and installed in Lab B-147/151 at SRTC. The contained JY Model Ultima 170-C ICP-ES has been tested and compared to current ADS ICP-ES instrumentation. The testing has included both performance tests to evaluate instrumental ability, and the measurement of matrix standards commonly analyzed by ICP-ES at Savannah River. In developing operating procedures for this instrument, we have implemented the use of internal standards and off-peak background subtraction. Both of these techniques are recommended by EPA SW-846 ICP-ES methods and are common to current ICP-ES operations. Based on the testing and changes, the JY Model Ultima 170-C ICP-ES provides improved performance for elemental analysis of radioactive samples in the Analytical Development Section.

Keywords: ICP-ES, waste tank analysis, RCRA

2.0 Introduction

2.1 Background

Late in FY 1998, ADS received capital funding (project S-W281) to purchase a contained Inductively Coupled Plasma Emission Spectrometer (ICP-ES) for radioactive sample analysis. The new instrument replaced the existing contained ARL 3580 ICP-ES, which was 15 years old. The new instrument was built by Jobin Yvon (JY) in France and is installed in laboratory B-147. A series of performance tests detailed in the specifications were performed prior to awarding the bid. These tests included spectral resolution, dynamic range, short and long term stability, sensitivity and interference control. The tests were also performed on the completed instrumentation in France and following installation at SRTC. JY had difficulty with several of the tests and spent about 6 months at SRTC reconfiguring the instrument and completing the tests. This report will document subsequent testing performed at SRTC to confirm accurate analyses.

2.2 Instrument Description

The instrument is an Inductively Coupled Plasma Emission Spectrometer (ICP-ES) with a 1.5 kWatt 40 MHz solid-state generator contained in a radiological fume hood. The spectrometer section of the instrument consists of a polychrometer for simultaneous analysis of 30 wavelengths and a monochrometer for wavelength flexibility. The monochrometer is a high-resolution design using a 1.0-m focal length Czerny-Turner (CZ) configuration, which covers from 120 nm - 800 nm with an argon purge to remove absorbing contaminants. The monochrometer uses a 2400 g/mm grating in the second order for 120-320 nm, resulting in a (Δ λ) resolution of 0.005-0.006 nm, full-width at half max (FWHM) and the same grating in first order from 320-800 nm resulting in resolution of 0.010-0.012 nm. Light is then measured with a high-dynamic range detection system (HDD) photomultiplier tube (PMT), which can vary the gain to accommodate a wide variety of intensities. The polychrometer uses a Paschen-Rungen mount (Rowland Circle) design with 0.5-m focal length and a 3000 g/mm grating in first order. The polychrometer also contains a flat-field segment to detect Na, Li and K. Table A-1 (Appendix) lists some of the elements/wavelengths on the polychrometer. The two main advantages to the polychrometer are speed and thermal stability. The main disadvantages are poorer resolution and stray light rejection. Thus, the monochrometer has better sensitivity while the polychrometer is more stable.

2.3 SRTC Hood Modifications

The design of the radiological fume hood in B-147 was found to be inadequate for the needs of SRTC. The radioactive fume hood had several concerns, including inadequate viewing into the hood and a large amount of torque on the glass window for stabilization. Jerry McCarty designed a new window, sash and frame, which were subsequently built and welded together by the machine shop and a local area vendor. The new equipment has been successfully installed in lab B-147. Minor modifications were also made to the brackets and counterweights for easier sash movement.

3.0 SRTC Instrument Testing

ADS evaluated the system for sensitivity, dynamic range, short and long term stability and spectral interference. The tests were similar to the performance tests, but under typical operating conditions (i.e. MDL's were measured for polychrometer lines rather than for optimum detection limits). Testing was also performed to identify typical problems such as PMT overrange and document polychrometer peak locations. The tests are listed in Table 2, and a complete listing of the results are available in Notebook WSRC-NB-2000-120. Most elements showed good stability and reasonable sensitivity. Corrective actions were taken for those elements with poor stability or sensitivity. Several operational changes were made due to the new instrumentation. These operational changes include background correction, gain settings on PMT's, use of guassian mode of peak calculation and use of an internal standard.

3.1 Initial Documentation

Initial tests were performed to document ICP performance after installation. We measured the signal and Relative Standard Deviation (%RSD) for 10 mg/L analyte, background intensity, detection limits and polychrometer position location with centering on Cr for a variety of wavelengths. This initial documentation will provide a baseline to evaluate performance over time. This documentation should also help evaluate problems during instrument breakdown.

3.2 Spectrometer Resolution

The JY ICP performed very well on the resolution performance tests at SRTC and France. Results demonstrated the 0.005-0.006 nm resolution in second order and 0.010-0.012 nm resolution in first order. We found no need for further testing on the resolution. The results are included below.

Table 1. Performance Test 3.1.1 Resolution

Description	Bid Package	SRTC Results
FWHM of Al 167 nm	0.0044 nm	0.0044 nm
Resolution of Tl doublet at 190.84	0.005 nm	0.00489 nm
Fe 310.04 - 3 peaks should be resolved and 4th partially resolved	ok	ok
As and Cd resolved at 228.802	resolved ($\Delta\lambda = 0.0043$)	Resolved ($\Delta\lambda = 0.0042$)
Ce and Fe resolved at 395.25 nm	resolved ($\Delta\lambda = 0.0068$)	Resolved ($\Delta\lambda = 0.010$)
Nd and Ce resolved at 401.22 nm	resolved ($\Delta\lambda = 0.009$)	Resolved ($\Delta\lambda = 0.010$)

3.3 ICP Wavelength Stability

One of our concerns was stability of the analytical signal. There were no stipulations for ICP operating conditions in the performance tests; thus, the instrument was run with slits at maximum during testing. ICP sensitivity and interference is significantly hampered by operation in this mode. Also, SRTC has temperature fluctuations, which can significantly impact ICP stability. We performed our own stability tests to obtain a true picture of ICP long term and short term stability. Our tests showed good short-term stability for performance times less than two hours. Long-term stability was very good for polychrometer elements, but very poor for monochrometer elements.

We believe that temperature instability was a major cause of poor results on several of the performance tests at France and SRTC. The result is that monochrometer wavelengths significantly move during operation of the instrument (see Figure 1). This instability can cause as much as a 50% decrease in signal after 8 hours.

Temperature instability is not evident on the polychrometer, even after 9 hours of run time. We must use an alternate mode of peak calculation called the guassian mode to prevent recalibration every hour or two for monochrometer wavelengths. For this method, 9 points are collected over the spectral region and a guassian curve is drawn from the best 5 points. If the wavelength shifts, the program should still find the maximum intensity of the peak. We are hopeful that recent modifications of the ventilation ducts in B-147/151 will improve temperature instability and allow other calculation methods.

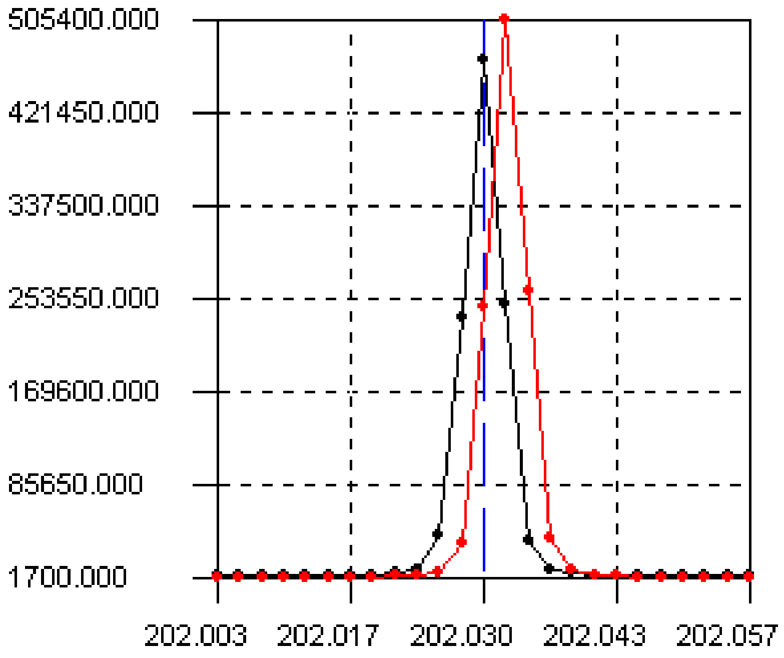

Figure 1. Change in monochrometer wavelength position of Molybdenum 202.03 nm from 9:00 (red) to 5:00 (black) during constant operation.

3.4 Background Interference

The existing ARL 3580 instrument had very good rejection of stray light, which has enabled SRTC to avoid using background correction until now. The JY polychrometer has approximately 30 times the stray light of the ARL. Table 2 compares the P 178.225 nm intensities on the ARL 3580 and the JY ICP-ES instruments. Some of the interference, i.e. Mo, is from direct overlap from a nearby wavelength; however, most of the increases in signal are from an increased background level caused by inadequate rejection of stray light. This increased background would cause inaccurate measurements for trace analysis. Background correction is a common practice in ICP-ES to eliminate this problem. Two points on either side of the peak are measured, averaged and subtracted from the peak. However, this is a significant change from our previous "hot" operation. The CTF over the instrument will need to be cognizant of background interference biasing numbers low. We have looked at interference on the polychrometer elements and selected the best correction positions based on common matrices and interference intensity.

Table 2. Comparison of measured concentration of ARL 3580 and JY ICP-ES instruments for P at 178 nm. High concentrations are mostly the result of background interference, which can be eliminated with background subtraction.

Solution	JY ICP-ES	ARL ICP-ES	JY with Bk Corr
[1]P 10 mg/L	7.90	10.0	9.12
Mn 100 mg/L	11.4	0.383	0.161
Fe 100 mg/L	3.24	0.090	-0.003
Mo 100 mg/L	0.854	0.292	0.579
Zr 100 mg/L	1.52	0.025	0.038
Ti 100 mg/L	0.46	0.042	0.014
Sn 100 mg/L	0.09	0.026	-0.010

[1] Instrument was calibrated with High Purity mutielement standard: ADS Mix 1 Solution A. Low value for JY ICP indicates interference from Mn and Fe in standard.

3.5 Gain and Internal Standards

We have made other modifications to the operation of the instrument to accommodate the needs of SRTC. First, gain settings on the PMT's in the polychrometer were set at the factory for optimum detection limits rather than dynamic range. We have reset the gains in several cases to measure higher concentrations typical of ADS solutions. For example, Si could measure a maximum of 20 mg/L without PMT over-range (requiring additional dilution for successful quantitation). We have reset the gain to measure at least 100 mg/L.

Second, we have added the use of an internal standard. This change should improve analysis of high concentrations of salt. At first, we attempted to use scandium on the monochrometer as an internal standard; however, the JY software automatically shifts from the guassian mode to peak height mode. We used Ce 399.924 nm on the polychrometer as an internal standard for Comparison Testing (Section 4.0). We have added a Scandium channel to the polychrometer since that time for internal standard correction.

4.0 SRTC Comparison ICP-ES Testing

Common analytical samples were analyzed on the current SRTC ICP-ES systems, "cold" ICP-ES (Optima 3000) and "hot" ICP-ES (ARL 3580), and compared to the JY. All samples and standards were non-radioactive and represent the wide range of samples analyzed by ADS. The results are split into common samples (Section 4.1) from selected ADS customers and solid and liquid standards (Section 4.2) from various labs.

4.1 ICP-ES Comparison of Common Samples

We selected two sets of samples for analysis by the JY: 300170118-300170129 and 300166455-300166465. These samples were selected because they had a relatively small number of elements and were representative of the high salt samples typically analyzed by ADS. The samples were run at 1000-fold dilution to measure sodium and 100-fold dilution to measure aluminum and silicon. The results for samples 170118-170129 are compiled below in Tables 3 and 4.

Table 3. Comparison of sodium and silicon analysis with both JY and Optima Instruments. Concentrations are measured in units of mg/L.

Sodium Analysis				Silicon Analysis		
Sample ID	JY	Optima	% Difference	JY	Optima	% Difference
170118	77000	80700	-4.7	116	97	18
170119	77200	80600	-4.3	128	107	18
170120	78200	81000	-3.5	214	193	10
170121	78000	80100	-2.7	217	201	7.5
170122	77800	81900	-5.1	401	376	6.4
170123	78700	82400	-4.6	405	384	5.4
170124	81700	84500	-3.4	119	108	9.2
170125	81800	84900	-3.7	112	105	6.6
170126	82700	86500	-4.5	229	219	4.2
170127	81100	82700	-2.0	205	197	4.2

170128	82000	86800	-5.7	346	330	4.7
170129	82000	86300	-5.1	321	319	0.8

Table 4. Comparison of aluminum analysis with JY and Optima ICP-ES Instruments. Concentrations are measured in units of mg/L.

Al Analysis			
Sample ID	JY	Optima	% Difference
170118	3410	3330	2.4
170119	3490	3440	1.4
170120	3220	3190	0.9
170121	3350	3320	0.9
170122	3260	3280	-0.6
170123	3140	3110	1.0
170124	4830	4790	0.8
170125	4970	4930	0.8
170126	4420	4400	0.5
170127	4290	4290	0.0
170128	4780	4700	1.7
170129	4360	4380	-0.5

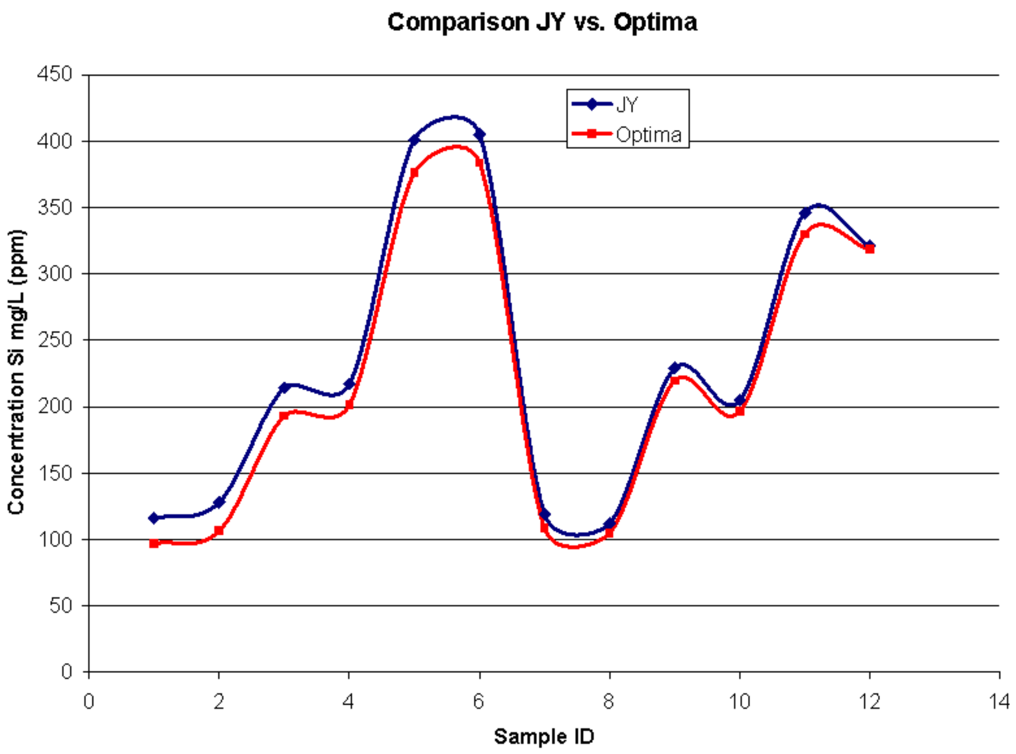

Figure 2. Comparison of Si measurements in samples 170118-170129 from Tank 38 Si removal studies.

For these samples, the two instruments compared well for Al and Na measurements. Theinstruments also compared well for Si except for the first three samples, which contain low levels of Si in a high sodium matrix. A high bias for low levels of Si was found for the JY instrument and is discussed in ADS document SRT-ADS-2002-0343. Figure YY shows a comparison plot of Si concentration in each sample.

A comparison of samples 166455-166465 was also performed by the two ICP-ES systems. The results are shown in Tables 5 and 6 below.

Table 5. Comparison of sodium and aluminum analysis with both JY and Optima Instruments. Concentrations are measured in units of mg/L.

Sodium Analysis	Aluminum Analysis

Sample ID	Optima	JY	% Difference	Optima	JY	% Difference
166455	160000	158000	-1.3	3440	3350	-2.8
166456	136000	135000	-0.7	37.0	31.0	-18.3
166457	134000	137000	2.2	222	207	-6.6
166458	137000	137000	0.0	452	436	-3.7
166459	137000	139000	1.5	634	607	-4.3
166460	150000	144000	-4.1	986	944	-4.4
166461	150000	150000	0.0	1480	1410	-4.9
166462	155000	157000	1.3	1980	1880	-5.3
166463	168000	161000	-4.3	2210	2070	-6.6
166464	163000	165000	1.2	2130	2020	-5.5
166465	170000	166000	-2.4	2060	1940	-5.7

Table 6. Comparison of silicon analysis with JY and Optima ICP-ES Instruments. Concentrations are measured in units of mg/L.

Si Analysis			
Sample ID	Optima	JY	% Difference
166455	2980	2970	-0.4
166456	80.3	79.4	-1.1
166457	230	222	-3.6
166458	437	413	-5.5

166459	597	561	-6.1
166460	886	850	-4.2
166461	1290	1220	-5.3
166462	1660	1570	-5.4
166463	1810	1690	-6.9
166464	1680	1580	-6.4
166465	1570	1470	-6.8

These samples had a much higher variation in Si and Al concentration, but the measurements for these elements were very good with the JY instrument. In all cases, except for Al in sample 166456, the results were within 7% of the concentration found by the current ADS "non-radioactive" ICP-ES. In the single anomalous case, Al concentration after dilution was very low, and the difference is within the expected error for such a low measurement.

4.2 ICP-ES Comparison of Common Standards

While the results of section 4.1 demonstrated the consistency in measurement between the two instruments, accuracy can only be demonstrated on standard materials with known concentrations. Nine different solid and liquid standards traceable to NIST were prepared and analyzed by all three ADS ICP-ES instruments for comparison. The results are shown in Tables 7-15 below. The results demonstrate very good accuracy for the elements measured. There are a few exceptions to note. First, Aluminum measured low for the BCR sludge standard for all three instruments, most likely due to incomplete dissolution. Second, analyses of trace components (i.e. Cd) in solids and drinking water were difficult due to the low concentration in the final solution. Lastly, line selection on the polychrometer played a significant role in the analysis. Trace levels of barium consistly measured high on JY and ARL ICP�s due to the use of different wavelength from the Optima instrument. Overall, the instrument performed very well on these standards and should improve, as the operators become more familiar with the instrument and its operation.

Table 7. Elemental analysis of LOAM-B soil sample digested by fusion and microwave ADS followed by ICP-ES analysis. Concentrations are measured in units of ug/g.

LOAM B � soil sample ADS 165864 (Concentration in ug/g)					
Element	JY	Optima	ARL	Expected	% Difference (JY)

Al	51000	49800	51600	51400	-0.8
Ca	3400	3470	3420	3390	0.3
Fe	27700	27600	29200	27400	1.1
Mg	3970	3730	4190	4040	-1.7
Mn	1570	1520	1670	1590	-1.3
Na	4630	4250	4710	4110	12.7
Si	363000	346000	352000	NA	NA
Sr	146	166	174	142	2.8
Ti	7700	7640	7630	(5700)	NA
Cd	116	93	105	92	26.1

Table 8. Elemental analysis of ARG glass standard by fusion and microwave digestions followed by ICP-ES analysis. Concentrations are measured in units of ug/g.

ARG Glass Std - ADS 165865 (Concentration in ug/g)					
Element	JY	Optima	ARL	Expected	% Difference (JY)
Al	24500	24600	24800	25000	-2.0
B	24300	26400	NA	26900	-9.7
Ba	983	803	969	790	24.4
Ca	10100	10300	10800	10200	-1.0
Cr	723	669	811	640	12.9
Fe	99700	98000	103000	97900	1.8
Li	15200	14800	15800	14900	2.0

Mg	5220	4800	5540	5200	0.4
Mn	14900	14200	15400	14600	1.7
Na	89500	84500	89100	85200	5.0
Ni	8270	8020	8250	8270	6.9
Si	227000	222000	240000	224000	1.3
Ti	7110	6900	7150	6900	3.0

Table 9. Elemental analysis of LRM glass standard by fusion and microwave digestions followed by ICP-ES analysis. Concentrations are measured in units of ug/g.

LRM Glass Std - ADS 165866 (Concentration in ug/g)					
Element	JY	Optima	ARL	Expected	% Difference (JY)
Al	51600	50800	52700	50600	2.0
B	22400	24700	25400	24800	-9.0
Ca	3900	3920	3690	3830	1.8
Cd	1450	1420	1450	1380	5.1
Cr	1470	1360	1390	1310	11.9
Fe	10300	10300	10400	9940	4.2
Li	522	512	485	497	4.9
Mg	660	545	648	615	7.3
Mn	601	579	595	608	-1.2
Na	161000	156000	163000	153000	5.6
Ni	1610	1500	1360	1460	10.2

Pb	815	904	672	891	-8.6
Si	263000	241000	260000	257000	2.3
Ti	657	622	607	629	4.3
Zr	7710	7100	7290	6740	14.4

Table 10. Elemental analysis of BCR Sludge standard by fusion and microwave digestions followed by ICP-ES analysis. Concentrations are measured in units of ug/g.

BCR Sludge Standard - ADS 165867 (Concentration in ug/g)					
Element	JY	Optima	ARL	Expected	% Difference (JY)
Al	25900	24600	27600	47600	-45.6
Ca	92600	95600	98800	101000	-8.8
Cd	106	81	85	78	36.4
Fe	19400	19100	20300	18500	4.7
Mg	17000	15900	18000	19900	-14.6
Mn	608	571	633	588	3.4
Na	2190	2410	2220	2230	-1.6
Ni	330	316	246	280	17.9
P	28900	28900	31000	25700	12.2
Pb	1430	1230	1200	1270	12.6
Si	107000	103000	124000	107000	0.4
Ti	17100	16900	18000	17400	-2.0
Zn	4230	4080	3850	4060	4.2

Table 11. Elemental analysis of SRS Frit 202 by fusion and microwave digestions followed by ICP-ES analysis. Concentrations are measured in units of ug/g.

Frit 202 - ADS 165868 (Concentration in ug/g)					
Element	JY	Optima	ARL	Expected	% Difference (JY)
Al	1490	1920	1070	1800	-17.2
B	22800	24900	26900	24500	-6.9
Ca	2780	2870	2870	NA	NA
Fe	308	338	301	266	15.9
Li	31600	30300	32500	32100	-1.6
Mg	12500	11900	13100	11900	4.9
Na	46000	45000	47200	43900	4.8
Si	368000	356000	362000	356000	3.4
Ti	1650	1630	1640	NA	NA

Table 12. Elemental analysis of Drinking Water Standard from High Purity Standards by ICP-ES analysis. Concentrations are measured in units of mg/L.

Drinking Water Standard - ADS 165824 (Concentration in mg/L)					
Element	JY	Optima	ARL	Expected	% Difference (JY)
Al	0.120	0.132	0.123	0.120	-0.1
Ba	0.044	0.051	0.050	0.050	-12.7
Ca	31.2	34.9	36.5	35.0	-10.8
Cd	0.007	0.011	0.013	0.010	-30.0

Cr	0.019	0.021	0.041	0.020	-5.0
Cu	0.018	0.024	0.020	0.020	-9.5
Fe	0.094	0.099	0.104	0.100	-6.0
Mg	8.81	9.22	8.99	9.00	-2.1
Mn	0.038	0.040	0.040	0.040	-5.0
Na	5.98	6.42	6.09	6.00	-0.3
Ni	0.060	0.060	0.062	0.060	0.0
P	<0.012	<0.076	<0.035	NA	NA
Pb	<0.066	<0.077	0.070	0.040	NA
Si	<0.008	<0.014	0.114	NA	NA
Sr	0.24	0.26	0.25	0.25	-5.2
Ti	0.001	<0.016	<0.001	NA	NA
Zn	0.066	0.077	0.069	0.070	-5.7

Table 13. Elemental analysis of Hanford Envelope A Simulant by ICP-ES analysis. Concentrations are measured in units of mg/L. No standard values available.

Envelope A Simulant - ADS 165825 (Concentration in mg/L)			
Element	JY	Optima	ARL
Al	1060	954	1260
B	2.09	2.49	3.30
Ba	<0.08	<0.12	<0.03
Ca	3.01	3.04	3.22

Cd	<0.06	<0.14	0.132
Cr	57.6	57.6	68.7
Cu	<0.40	<0.50	0.058
Fe	<0.04	<0.44	0.133
Mg	<0.2	<0.84	0.59
Mn	<0.007	<0.09	0.032
Na	11300	10700	11000
Ni	<0.32	<0.62	0.15
P	19.1	19.6	21.1
Pb	<5.9	<6.9	2.69
Si	6.8	16.7	10.5
Sr	<0.004	<0.020	0.021
Ti	0.050	<1.4	0.266
V	NA	<1.3	0.090
Zn	<0.30	<3.7	0.45
Zr	<0.050	<0.48	0.062
Ag	NA	<3.0	0.080

Table 14. Elemental analysis of SPEX Multi-Element Standard by ICP-ES analysis. Concentrations are measured in units of mg/L.

SPEX Multi-element Standard - ADS 165826 (Concentration in mg/L)					
Element	JY	Optima	ARL	Expected	% Difference (JY)

B	494	535	532	500	-1.2
Li	483	493	519	500	-3.4
Mg	482	496	543	500	-3.6
Na	508	517	530	500	1.6
P	498	502	530	500	-0.4
Si	476	459	558	500	-4.8
Ti	479	510	529	500	-4.2

Table 15. Elemental analysis of In-house Standard by ICP-ES analysis. Concentrations are measured in units of mg/L.

ADS Standard 1 - ADS 165827 (Concentration in mg/L)					
Element	JY	Optima	ARL	Expected	% Difference (JY)
Al	501	490	586	500	0.20
Na	2360	2200	2470	2200	7.3
Si	208	208	242	200	4.0
Pb	9.55	9.87	11.9	10.0	-4.5
Ag	NA	9.67	14.3	10.0	NA
Ba	9.89	10.0	11.2	10.0	-1.1
Cd	9.80	10.0	11.2	10.0	-2.0
Cr	9.58	9.82	12.0	10.0	-4.2
Be	NA	9.66	NA	10.0	NA

5.0 Data Export and Workup

Data work-up for the JY ICP-ES was accomplished using a new Excel Macro (designed by ADS) called "JY_NewMacro_ves1" and Excel computational workbooks called "JY Template Rev 1.xls" and "JY Template Solids Rev 1.xls." The macro is documented in Notebook WSRC-NB-2001-120 pp. 56-64. For routine operations of the instrument, an excel template "JY _Liquid_Template_U_Poly.xls" is used in tandem with "JY_MDL_Master.xls." The spreadsheets have been designed by ADS and confirmed with ICP-ES data that has been calculated by hand.

6.0 Conclusions

While installation of the instrument was time-consuming for the vendor and ADS, the overall result was a reliable instrument for routine measurements of radioactive samples at SRTC. In developing operating procedures for this instrument, we have implemented the use of internal standards and off-peak background subtraction. Both of these techniques increased the accuracy of results from the ICP-ES for samples with difficult matrices. Improved accuracy has been demonstrated by the performance tests described in section 4.0 of this document. Overall, the instrument performed very well on these standards and should improve, as the operators become more familiar with the instrument and its operation.

Appendix

These tables are included to record performance and set parameters at the beginning of operation.

Table A-1. Background correction positions for polychrometer wavelengths.

Element	Wavlength (nm)	Left Background (nm)	Right Background (nm)
Al	308.215	0.0127	0.0199
B	208.959	0.0199	0.0199
Cd	226.502	0.0127	0.0199
Ce	399.924	0.0199	0.0199
Cr	205.599	0.0199	0.0199
Cu	224.700	0.0199	0.0199
Fe	259.940	0.0127	0.0199

K	766.490	0.0199	0.0199
Mn	257.610	0.0199	0.0199
Na	589.582	0.0199	0.0199
Ni	216.552	0.0127	--------
P	178.225	0.0199	0.0199
Pb	220.353	0.0199	0.0199
Si	251.611	0.0127	0.0199
Zn	213.856	0.0199	0.0199

Table A-2. Detection limits for selected JY wavelengths using Guassian mode for monochrometer wavelengths.

Element	Wavlength (nm)	Poly/Mono	MDL (mg/L)
Al	308.215	Poly	0.093
B	208.959	Poly	0.013
Ba	230.424	Poly	0.008
Be	313.042	Mono	0.002
Ca	393.367	Poly	0.001
Cd	226.502	Poly	0.006
Cr	205.599	Poly	0.012
Cu	224.700	Poly	0.005
Fe	259.940	Poly	0.004
K	766.490	Poly	1.16

La	408.672	Poly	0.001
Li	670.784	Poly	0.005
Mg	279.553	Poly	0.0004
Mn	257.610	Poly	0.0007
Na	589.582	Poly	0.022
Ni	216.552	Poly	0.032
P	178.225	Poly	0.111
Pb	220.353	Poly	0.038
S	181.978	Mono	0.024
Sb	217.581	Mono	0.009
Si	212.412	Mono	0.031
Si	251.611	Poly	0.055
Si	288.158	Mono	0.041
Sn	189.989	Mono	0.1
Sr	407.771	Poly	0.0004
Ti	334.940	Poly	0.0012
V	292.402	Mono	0.002
Zn	213.856	Poly	0.003
Zr	349.621	Poly	0.005
Zr	343.823	Mono	0.010
Ce	413.765	Mono	0.094
Ce	413.380	Mono	0.097

Eu	381.965	Mono	0.0006
La	398.852	Mono	0.003
La	379.478	Mono	0.0018
Nd	406.109	Mono	0.010
Nd	401.225	Mono	0.003
Pr	414.311	Mono	0.012
Sm	359.262	Mono	0.006
Br[1]	76.557	Mono	0.630
Cl[1]	67.362	Mono	1.100
Hg	253.652	Mono	0.008
U	385.958	Poly	1.12

[1] Cl and Br wavelengths are 1/2 of true wavelengths.

Table A-3. Optimized gain settings for the JY ICP-ES instrument.

Element	Channel	Factory Gain (on)	Factory Gain (off)	New Gain (on)	New Gain (off)
Ba	11	6,5,4,3,2	1	6,5,3,1	4,2
Ca	22	6	5,4,3,2,1	4	6,5,3,2,1
Cd	10	6,5,4,3	2,1	6,5,4	3,2,1
La	25	6,4,3,2	5,1	6,4,3,2	5,1
Li	27	6,5,4	3,2,1	6,5,3	1,2,4
Mg	15	6	5,4,3,2,1	3,4	6,5,2,1
Si	12	6,5,4,3,2	1	6,4,2	5,3,1

Sr	24	6,4,2,1	3,5	4,3	6,5,2,1
Zn	6	6,5,4,2	1,2	6,4,3	5,1,2
Zr	20	6,5,4	3,2,1	3,4	6,5,1,2