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Performance Test and Validation Evaluation for the Neutron Slab Counter

This document is approved for public
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**Performance Test and Validation Evaluation
for the Neutron Slab Counter**

Date Issued - December 2013

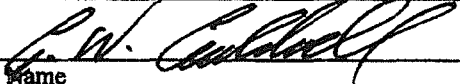
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APPROVALS

Performance Test and Validation Evaluation for the Neutron Slab Counter	UCOR-4527
	December 2013

USQD Review Determination	☒ USQD ☐ UCD ☐ CAT X ☐ Exempt (Select Criteria below.) USQD/UCD/CAT X No.: <u>USQD-MS-CX-REPORTS-1074 Rev. 1</u>	
Exemption Criteria	☐ (1) Non-Intent Change ☐ (2) DOE-Approved Document ☐ (3) Clearly no impact on Nuclear Facilities ☐ (4) Chief Financial Officer, Internal Audit, Labor Relations, Legal, Public Affairs, or Project Controls Organization Document	
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Exhibit L Mandatory Contractor Document	☒ No (No PCCB Reviewer Signature Required) ☐ Yes (Requires review by the Proforma Change Control Board.)	
PCCB Reviewer:	_____ Name	
	_____ Date	

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ACRONYMS

DQO	data quality objective
MCNP	Monte Carlo N-Particle Transport Code
MDA	minimum detectable activity
NDA	nondestructive assay
NSC	neutron slab counter
PTVE	Performance Test and Validation Evaluation
PTVP	Performance Test and Validation Plan
PTVR	Performance Test and Validation Report
RSD	relative standard deviation
TMU	total measurement uncertainty
UNCS	Uranium Neutron Counting System
VDC	volts direct current
WRM	Working Reference Material

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1. Introduction

This Performance Testing and Validation Evaluation (PTVE) reviews and analyzes the data collected with the Neutron Slab Counter (NSC) according to the Performance Test and Validation Plan (PTVP, UCOR-4443) and reported in the NSC Performance Test and Validation Report (PTVR, NDA-13-0622). The NSC was designed for quantitative Nondestructive Assay (NDA) measurements of compressor volutes from the K25/K27 Buildings.

The NSC PTVP (UCOR-4443) prescribed a methodology and set of field measurements to determine the NSC system efficiency, calibrate the system, perform verification measurements, define the components of the system's total measurement uncertainty, and perform a calibration confirmation measurement.

All of the required measurements of the NSC PTVP (UCOR-4443) were completed according to the *Calibration of NDA Equipment* Procedure (PROC-DE-0714) and the *Quantitative Measurements Using the Neutron Slab Counter* Procedure (PROC-DE-0723). Following the completion of this PTVE, if the data quality objectives (DQO) of the NSC PTVP (UCOR-4443) are met, a commissioning report will be prepared which specifies the limits of use of the NSC.

1.1 INITIAL TROUBLESHOOTING

On the first day of measurements, to meet the requirements of the NSC PTVP (UCOR-4443); 9/9/2013, control measurements were being performed to establish a measurement control baseline for the measurement control computer program (MCCP), according to PROC-DE-0714. The NSC ID where the PTVP measurements were performed is NSC1. The NSC1 components for the initial measurements on 9/9/2013 were:

- Upper E-600 Scaler/Analyzer: 19231 (1015)
- Upper Detector: K333172
- Lower E-600 Scaler/Analyzer: (1017)
- Lower Detector: K332795

The certificate for the CF-252 source, FTC-CF-835, is provided in Appendix A. The data for the first two control measurements are presented in Table 1.

Table 1 NSC 1 Measurement Control Data 9/9/2013

Type	Log Date	Log Time	Upper Slab K333172 (counts)	Lower Slab K332795 (counts)
QA	09/09/13	10:31	105000	72400
QA	09/09/13	10:46	106000	1200

Due to the low counts from the lower slab detector, a faulty E-600 scaler was suspected. The E-600 unit (1017) was replaced with a different E-600 (19232: 1016). The process of establishing a measurement control baseline was restarted on 9/9/2013, and measurements with the calibration source at calibration point locations 9 and 1 were performed with the corresponding background measurements (NDA-13-0622). On 9/10/2013, while reviewing the data collected on 9/9/2013, a low count value was observed for the lower slab detector (K332795) with the calibration source placed at calibration point location 1. The

observed count value with the calibration source at calibration point location 1 was only 46% of the background value. Troubleshooting of NSC1 was conducted with a determination that the lower slab detector K332795 was malfunctioning. The lower slab detector was replaced on 9/10/2013.

Once the problem was corrected, the configuration of NSC1 was fixed for the duration of the testing and consists of the following components:

- Upper E-600 Scaler/Analyzer: 19231 (1015)
- Upper Detector: K333172
- Lower E-600 Scaler/Analyzer: 19232 (1016)
- Lower Detector: K333772

1.2 ORGANIZATION OF DOCUMENT

The Instrument and Method Qualification section of the NSC PTVP (UCOR-4443) defines requirements for instrument setup, calibration, calibration verification and performance tests, and calibration confirmation. Instrument setup is discussed in section 2, and the calibration measurements performed are described in section 3. Section 3 includes the data collected from the NSC as well as the data generated from MCNP. The resultant efficiencies are then determined based on the methodology prescribed in the NSC PTVP (UCOR-4443). The calibration verification and performance test results are presented in section 4, and the calibration confirmation results are presented in section 6. Section 5 contains an analysis of the data collected to determine the Minimum Detectable Activity (MDA) and Total Measurement Uncertainty (TMU) of the NSC based on the methodology in the NSC PTVP (UCOR-4443). A summary of the presentation of results and analyses of this PTVE is contained in section 7 and the applicable references are listed in section 8.

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2. INSTRUMENT SETUP

Detectors and electronics were verified to be functioning properly, including the high voltage settings on the detectors, at the start of the NSC PTVP (UCOR-4443) measurement cycle.

The ID number of the NSC where all measurements were performed to meet the requirements of the NSC PTVP (UCOR-4443) was NSC1 and the critical electronic components configured for the duration of the NSC PTVP (UCOR-4443) measurements are:

- Upper E-600 Scaler/Analyzer: 19231 (1015)
- Upper Detector: K333172
- Lower E-600 Scaler/Analyzer: 19232 (1016)
- Lower Detector: K333772

The identified measurement control source at the start of the PTVP measurement cycle was FTC-CF-835 (appendix A). The measurement control source is positioned at the geometric center of the two slab detectors using a source holder attached to a scaffold pole. This positioning can be easily replicated for successive control measurements.

Following the steps as written in PROC-DE-0714, a measurement control range was established for NSC1. These data are provided in Table 2. Each control measurement was performed for 300 seconds. The plot produced by the MCCP after entry of these data is shown in Fig. 1. Based on the data collected, the mean value, 2σ , and 3σ were established as shown in Table 3.

Table 2. Initial measurement control data – NSC 1, FTC-CF-835

Type	Log Date	Log Time	Upper Slab K333172 (counts)	Lower Slab K333772 (counts)	Total (counts)	Decay Corrected Total (counts)
QA	09/11/13	8:14	103000	98000	201000	1153500
QA	09/11/13	8:19	103400	97500	200900	1152900
QA	09/11/13	8:26	102000	96600	198600	1139700
QA	09/11/13	8:32	104500	99100	203600	1168400
QA	09/11/13	8:38	101700	95800	197500	1133400
QA	09/11/13	8:44	103500	97700	201200	1154600

Table 3. Initial measurement control ranges established for NSC 1

Daily Limits	
Limits	Count Rate (total measured counts)
3σ	206900
2σ	204800
1σ	202600
mean	200500
-1σ	198300
-2σ	196200
-3σ	194000

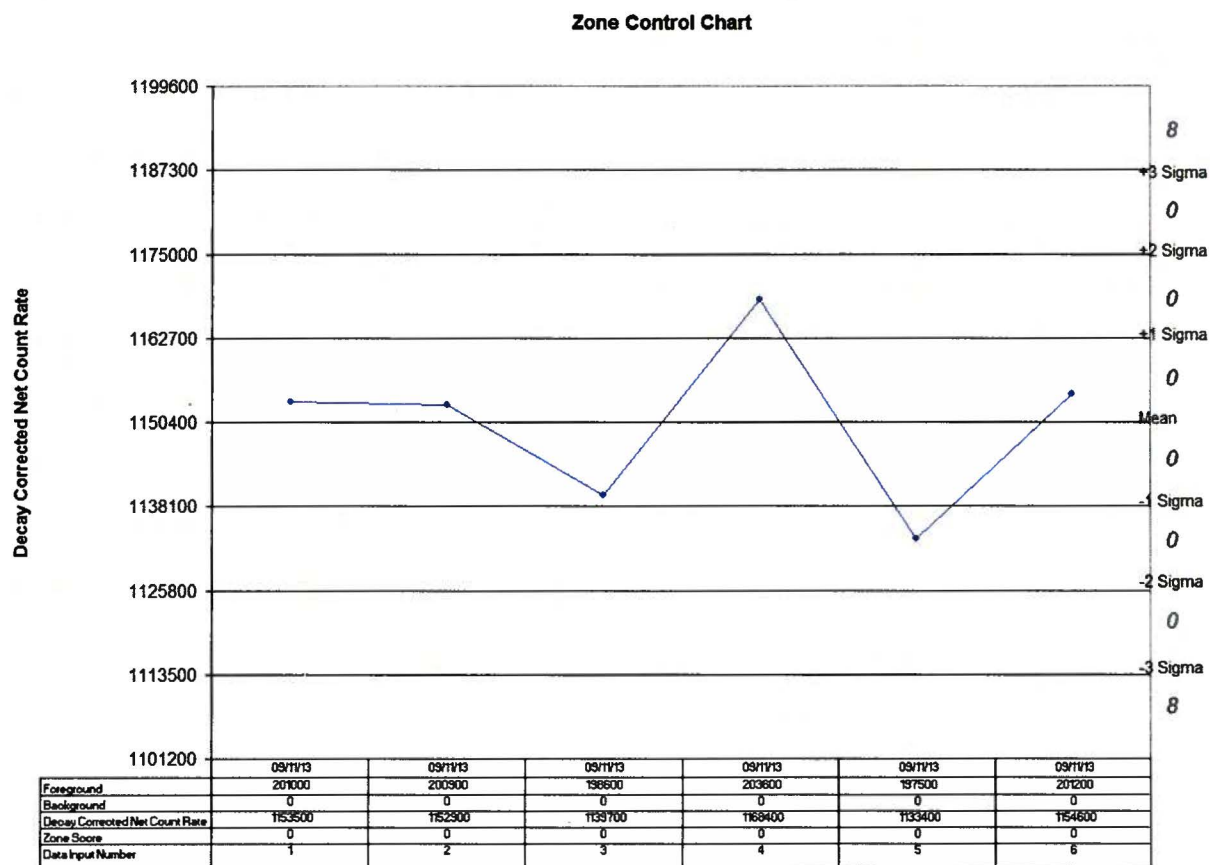


Fig. 1 NSC 1 initial QA measurements

3. CALIBRATION TEST RESULTS

3.1 CALIBRATION DATA

The calibration process outlined in the PTVP (Table 4, UCOR-4443) was formalized in the NDA Calibration Procedure (PROC-DE-0714) prior to the start of the NSC calibration measurements. The required measurements at the 11 calibration locations with the WRM3 fully hydrated UO_2F_2 source (appendix A) were performed from 9/11/13 through 9/16/13 and reported in the NSC PTVR (NDA-13-0622). The data are summarized in Table 4, and the specified locations are shown in Fig. 2. The x, y, and z coordinate values for each calibration point are specified with respect to an origin at the geometric center of the calibration space, point 10 (0, 0, 0). Two measurements were performed at calibration point locations 6 and 11. These data will be discussed in section 3.4.

Table 4. NSC Calibration Measurement Data (+/- 36 inches)

Location	x (inches)	y (inches)	z (inches)	Date	Upper Slab				Lower Slab			
					F_1^1 (counts)	t_{F_1} (s)	B_1^3 (counts)	t_{B_1} (s)	F_2^2 (counts)	t_{F_2} (s)	B_2^4 (counts)	t_{B_2} (s)
1	-36	0	6.25	9/11/13	3160	3600	2350	3600	2940	3600	2650	3600
2	-36	0	-6.25	9/12/13	3140	3600	2700	3600	3130	3600	2720	3600
3	0	36	6.25	9/13/13	2940	3600	2470	3600	3130	3600	2710	3600
4	0	36	-6.25	9/13/13	2840	3600	2400	3600	3210	3600	2850	3600
5	36	0	6.25	9/11/13	2840	3600	2390	3600	2970	3600	2610	3600
6	36	0	-6.25	9/16/13	2690	3600	2310	3600	3000	3600	2620	3600
7	0	-36	6.25	9/13/13	2890	3600	2580	3600	3210	3600	2880	3600
8	0	-36	-6.25	9/13/13	2930	3600	2480	3600	3240	3600	2840	3600
9	0	0	6.25	9/11/13	3460	3600	2280	3600	3180	3600	2660	3600
10	0	0	0	9/12/13	3240	3600	2370	3600	3450	3600	2640	3600
11	0	0	-6.25	9/13/13	3040	3600	2340	3600	3770	3600	2760	3600
11	0	0	-6.25	9/12/13	4480	3600	2420	3600	3740	3600	2710	3600
6	36	0	-6.25	9/12/13	4730	3600	2440	3600	3270	3600	2730	3600

1. F_1 (c) is the total neutron count from the upper slab detector (K333172) collected within time t_{F_1} (s), with the WRM3 source at the specified calibration point.
2. F_2 (c) is the total neutron count from the lower slab detector (K333772) collected within time t_{F_2} (s), with the WRM3 source at the specified calibration point.
3. B_1 (c) is the total background neutron count from the upper slab detector (K333172) collected within time t_{B_1} (s), without the surrogate volute in place.
4. B_2 (c) is the total background neutron count from the lower slab detector (K333772) collected within time t_{B_2} (s), without the surrogate volute in place.

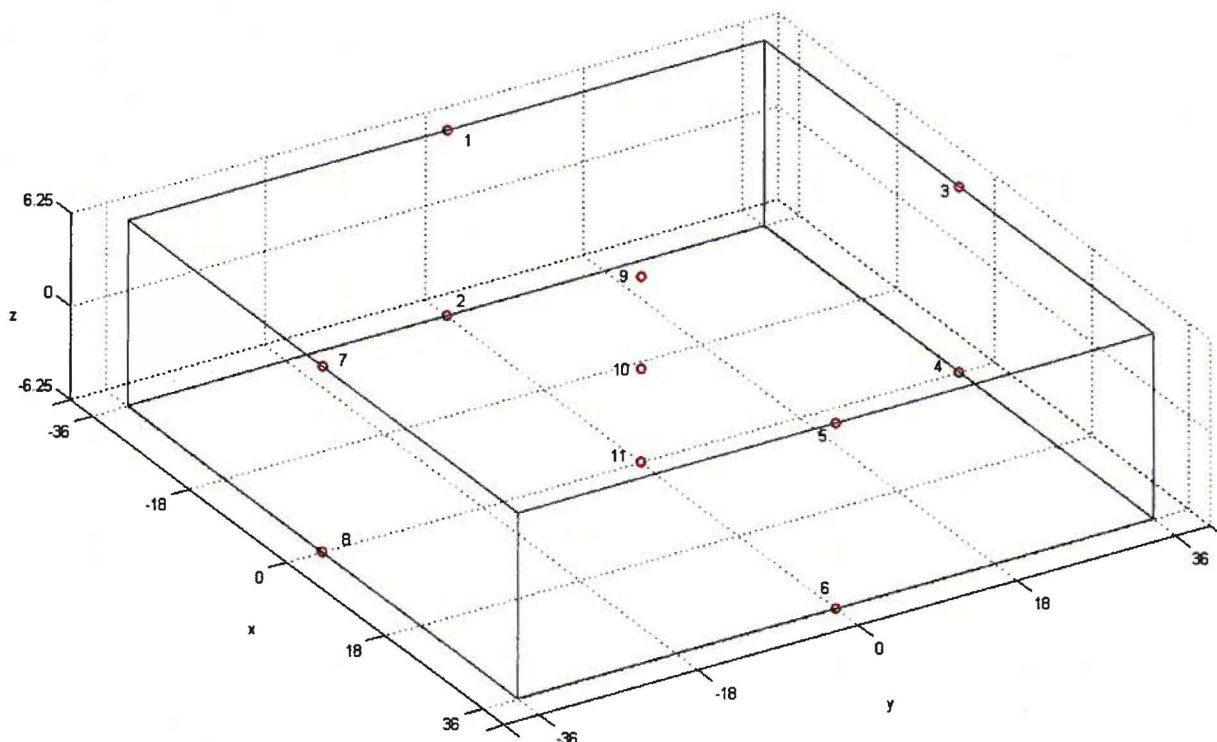


Fig. 2 NSC Calibration Point Locations (x, y, and z values are in inches)

Based on some preliminary analyses of the data collected at the 11 calibration points the percent difference between the measured efficiency and the Monte Carlo N Particle (MCNP) efficiency at some locations was higher than expected (see section 3.4). The standoff of each slab detector to the closest plane of the calibration space is 36 inches. The width of the calibration space is 72 inches. Calibration points 1 through 8 are at the edge of the calibration space. For measurements with the calibration source at the edges of the calibration space the observed variability in measured efficiency is expected to be greater than if the source were placed closer to the center of the calibration space. The efficiency profile across the calibration space is a bell-shaped curve and at the edges of the calibration space the efficiency profile curve has a steep slope. The calibration source placement was re-considered. The originally planned positions were specified to cover the entire counting volume of the NSC; however, the location of the holdup source material in compressor volutes will not extend to the outer edges of this volume.

A revised set of calibration points was defined which placed the calibration points at one half the distance from the center to the edge of the calibration space (i.e. ± 18 inches), the z axis values remained unchanged. Measurements were performed at the revised set of calibration points from 10/08/13 through 10/10/13 and reported in the NSC PTVR (NDA-13-0622). These measurements were performed under the NDA calibration procedure (PROC-DE-0714) that was effective at the time, which allowed for additional background and foreground measurements to be performed at the discretion of the NDA SME. A subsequent revision to the NSC PTVR (UCOR-4443) included the specification of the revised calibration point locations. The data collected at the revised set of calibration points are summarized in Table 5, and the specified locations are shown in Fig. 3.

All calibration measurements were performed with WRM3 at the specified locations as prescribed by the NSC PTVP (UCOR-4443). Each measurement was preceded by a background measurement and is bound by passing control measurements performed at the required frequency as specified in PROC-DE-0714. The control measurement data are documented in the NSC PTVR (NDA-13-0622).

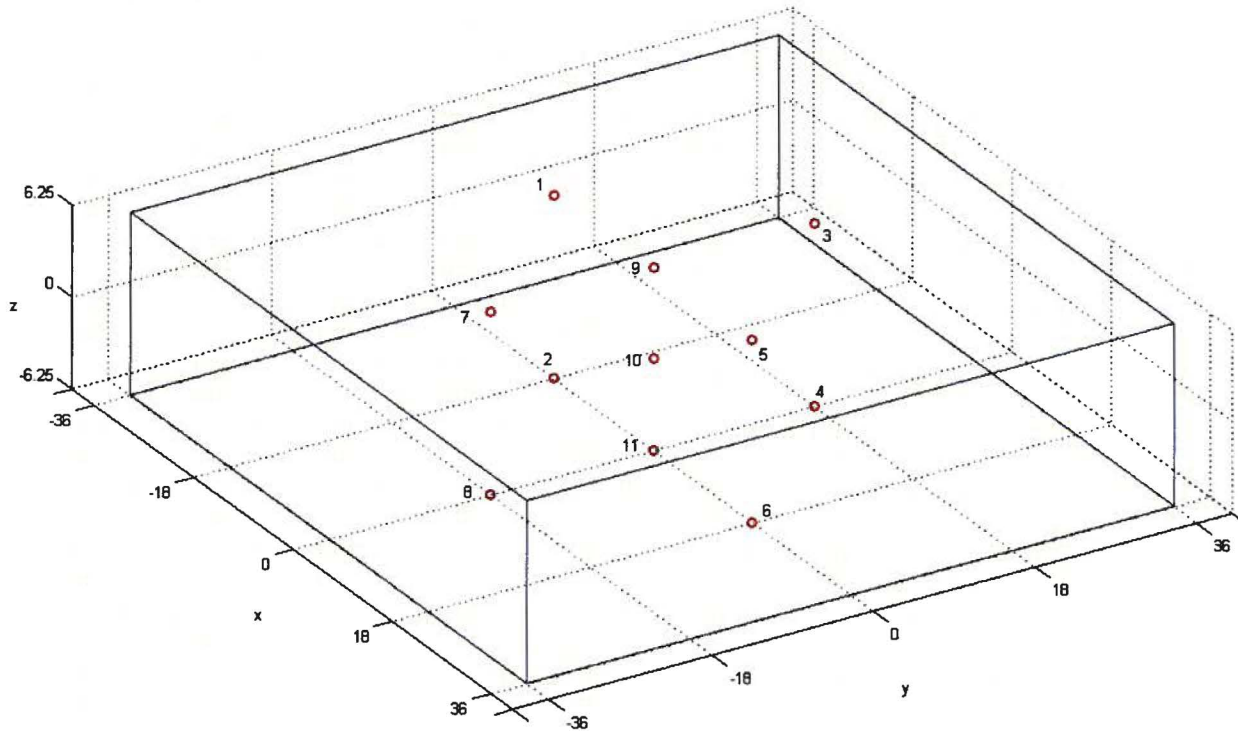


Fig. 3 NSC Revised Calibration Point Locations (x, y, and z values are in inches)

Table 5. NSC Calibration Measurements at Revised Calibration Points (+/- 18 inches)

Location	x (inches)	y (inches)	z (inches)	Date	Upper Slab				Lower Slab			
					F_1^1 (counts)	t_{F_1} (s)	B_1^3 (counts)	t_{B_1} (s)	F_2^2 (counts)	t_{F_2} (s)	B_2^4 (counts)	t_{B_2} (s)
1	-18	0	6.25	10/10/13	3200	3600	2430	3600	3200	3600	2700	3600
2	-18	0	-6.25	10/10/13	3030	3600	2350	3600	3670	3600	2760	3600
3	0	18	6.25	10/9/13	3180	3600	2330	3600	3200	3600	2680	3600
4	0	18	-6.25	10/9/13	2890	3600	2320	3600	3390	3600	2640	3600
5	18	0	6.25	10/10/13	3130	3600	2420	3600	3220	3600	2650	3600
6	18	0	-6.25	10/10/13	2900	3600	2370	3600	3580	3600	2600	3600
7	0	-18	6.25	10/9/13	3190	3600	2340	3600	3270	3600	2670	3600
8	0	-18	-6.25	10/9/13	2950	3600	2310	3600	3420	3600	2720	3600
9	0	0	6.25	10/8/13	3550	3600	2440	3600	3460	3600	2580	3600
10	0	0	0	10/8/13	3190	3600	2370	3600	3590	3600	2720	3600
11	0	0	-6.25	10/8/13	3150	3600	2450	3600	3810	3600	2760	3600

1. F_1 (c) is the total neutron count from the upper slab detector (K333172) collected within time t_{F_1} (s), with the WRM3 source at the specified calibration point.
2. F_2 (c) is the total neutron count from the lower slab detector (K333772) collected within time t_{F_2} (s), with the WRM3 source at the specified calibration point.
3. B_1 (c) is the total background neutron count from the upper slab detector (K333172) collected within time t_{B_1} (s), without the surrogate volute in place.
4. B_2 (c) is the total background neutron count from the lower slab detector (K333772) collected within time t_{B_2} (s), without the surrogate volute in place.

3.2 MCNP DATA FOR CALIBRATION SOURCE

The WRM3 source definition input to MCNP for the simulations at the 11 calibration points is provided in Table 6. The WRM3 source certificate is provided in Appendix A. The resultant count rates and efficiencies for the initial 11 calibration point locations (+/- 36 inches) are provided in Table 7 and for the revised set of calibration points locations (+/- 18 inches) in Table 8. The source definition for MCNP was distributed over the volume of the source material in the WRM3 containing cylinder (MCLinc 2008).

Table 6. WRM3 Source Definition

WRM3 Calibration Source	
g U-235/ g U	0.4552
g U-235/ g U-234	148.73
g U	231.90
g U-234	0.71
g U-235	105.60
g U-238	125.59
g H	3.93
g O	62.34
g F	37.02
g Total	335.19
U-234 (n/s) ¹	127.80
U-235 (n/s) ²	3.80
U-238 (n/s) ²	2.20
Total (n/s)	133.80

1. Based on n/s/g U-234 in fully hydrated UO₂F₂ from BJC/OR-2862
2. Based on n/s/g U-235 and n/s/g U-238 for UO₂F₂ from LANL 1991

Table 7. MCNP Simulation Results for NSC Calibration Point Locations (+/- 36 inches)

Location	x (inches)	y (inches)	z (inches)	Measured Count Rate (n/s)	Error (n/s)	$\mathcal{E}_{i,S,MCNP}$
1	-36	0	6.25	0.230454	0.0120	0.17224%
2	-36	0	-6.25	0.241601	0.0122	0.18057%
3	0	36	6.25	0.223394	0.0123	0.16696%
4	0	36	-6.25	0.220799	0.0127	0.16502%
5	36	0	6.25	0.225087	0.0120	0.16823%
6	36	0	-6.25	0.230922	0.0125	0.17259%
7	0	-36	6.25	0.222701	0.0122	0.16644%
8	0	-36	-6.25	0.223344	0.0127	0.16692%
9	0	0	6.25	0.516963	0.0084	0.38637%
10	0	0	0	0.487611	0.0088	0.36443%
11	0	0	-6.25	0.517973	0.0090	0.38712%

Table 8. MCNP Simulation Results for Revised Set of NSC Calibration Point Locations (+/- 18 inches)

Location	x (inches)	y (inches)	z (inches)	Measured Count Rate (n/s)	Error (n/s)	$\mathcal{E}_{i,S,MCNP}$
1	-18	0	6.25	0.405842	0.0094	0.30332%
2	-18	0	-6.25	0.412705	0.0096	0.30845%
3	0	18	6.25	0.405190	0.0095	0.30283%
4	0	18	-6.25	0.406517	0.0098	0.30382%
5	18	0	6.25	0.398682	0.0094	0.29797%
6	18	0	-6.25	0.412500	0.0096	0.30830%
7	0	-18	6.25	0.398427	0.0094	0.29778%
8	0	-18	-6.25	0.399405	0.0098	0.29851%
9	0	0	6.25	0.517303	0.0084	0.38662%
10	0	0	0	0.488279	0.0087	0.36493%
11	0	0	-6.25	0.516063	0.0086	0.38570%

3.3 MCNP DATA FOR VOLUTE EFFICIENCY

The source definition input to MCNP for the compressor volute simulations as prescribed in the PTVF are provided in Table 9 along with the resultant MCNP efficiencies. The simulations cover a range of source strengths and two U-235 enrichment values. The source material is fully hydrated UO_2F_2 ($\text{UO}_2\text{F}_2 \cdot 2\text{H}_2\text{O}$). In each case, the source material was represented as five point sources within the seal area of the compressor volute (one in the center and four at one-half the radius at the 3, 6, 9, and 12 o'clock positions).

Table 9. MCNP Source Definition and NSC MCNP Efficiency Results for Compressor Volute

²³⁵ U Enrichment (%)	Source (g) ¹								²³⁵ U/ ²³⁴ U Ratio ²	Source (n/s) ³				NNC Neutron Slab Detector		
	²³⁵ U	²³⁴ U	²³⁸ U	U	H	O	F	Total		²³⁴ U	²³⁵ U	²³⁸ U	Total	Measured Count Rate (n/s)	Error (n/s)	Efficiency (%)
3	25	0.16	808.17	833	14.1	224.0	133.0	1204.5	156.56	28.74	0.90	14.14	43.79	0.233884	0.0085	0.534149
	50	0.32	1616.35	1667	28.2	448.0	266.1	2409.0		57.49	1.80	28.29	87.57	0.467713	0.0085	0.534086
	100	0.64	3232.69	3333	56.5	896.1	532.2	4818.0		114.97	3.60	56.57	175.15	0.935858	0.0085	0.534333
	200	1.28	6465.39	6667	112.9	1792.1	1064.3	9636.1		229.95	7.20	113.14	350.29	1.870920	0.0085	0.534106
	400	2.55	12930.78	13333	225.8	3584.3	2128.7	19272.1		459.89	14.40	226.29	700.58	3.741820	0.0085	0.534103
	600	3.83	19396.17	20000	338.8	5376.4	3193.0	28908.2		689.84	21.60	339.43	1050.87	5.612790	0.0085	0.534108
	800	5.11	25861.56	26667	451.7	7168.6	4257.3	38544.3		919.78	28.80	452.58	1401.16	7.483680	0.0085	0.534106
	1000	6.39	32326.95	33333	564.6	8960.7	5321.7	48180.4		1149.73	36.00	565.72	1751.45	9.354580	0.0085	0.534104
20	25	0.16	99.84	125	2.1	33.6	20.0	180.7	153.35	29.34	0.90	1.75	31.99	0.170930	0.0085	0.534304
	50	0.33	199.67	250	4.2	67.2	39.9	361.4		58.69	1.80	3.49	63.98	0.341721	0.0085	0.534087
	100	0.65	399.35	500	8.5	134.4	79.8	722.7		117.38	3.60	6.99	127.96	0.683442	0.0085	0.534087
	200	1.30	798.70	1000	16.9	268.8	159.7	1445.4		234.75	7.20	13.98	255.93	1.366930	0.0085	0.534105
	400	2.61	1597.39	2000	33.9	537.6	319.3	2890.8		469.50	14.40	27.95	511.86	2.733880	0.0085	0.534109
	600	3.91	2396.09	3000	50.8	806.5	479.0	4336.2		704.26	21.60	41.93	767.79	4.100820	0.0085	0.534109
	800	5.22	3194.78	4000	67.8	1075.3	638.6	5781.6		939.01	28.80	55.91	1023.72	5.467760	0.0085	0.534109
	1000	6.52	3993.48	5000	84.7	1344.1	798.3	7227.1		1173.76	36.00	69.89	1279.65	6.834710	0.0085	0.534110

1. Source is UO₂F₂•2H₂O

2. BJC/OR-2862

3. 180 n/s/g U-234 (BJC/OR-2862), 0.036 n/s/g U-235 and 0.0175 n/s/g U-238 (LANL 1991)

3.4 EFFICIENCY CALCULATIONS

Given the measurement data collected for the originally specified calibration point locations as provided in Table 4, the net count rates of the calibration measurements were determined according to equation 3-1 of the NSC PTVP (UCOR-4443). Based on the WRM3 calibration source data (Table 6), the measured efficiency of the NSC at each of the 11 calibration point locations was determined according to equation 4-1 of the PTVP. The computed net count rates and measured efficiencies are provided in Table 10, along with the MCNP derived efficiency values for comparison.

The last two rows of data in Table 10 provide measured efficiencies considerably higher than that computed by MCNP at calibration point locations 11 and 6. These data were initially collected on 9/12/13, along with data for calibration point locations 2 and 10. The results for calibration point locations 2 and 10 are consistent with the MCNP derived values. In considering these two particular measurements and the overall calibration approach, the initial spacing of the calibration point locations was subject to review. The original spacing of the calibration point locations intended to cover the entire active volume based on a 90 degree field of view from the centerline of the slab detectors. This resulted in the spacing of the outer calibration point locations to +/- 36 inches from the geometric center of the NSC calibration space. Efficiency measurements are prone to higher uncertainty as the source is moved outward in the detector's field of view. Furthermore, the utility of the calibration measurements is in correcting the MCNP derived efficiency for the compressor volute; thus, while it is important to evaluate the measured vs. MCNP computed efficiencies at a sufficient number of points throughout the calibration space, the need for accuracy in the efficiency measurements is greater than the need to cover the entire active volume of the NSC calibration space. Furthermore, the initial point locations at +/- 36 inches are outside of the known volume of the compressor volute itself.

After considering these arguments, the decision was made to perform a second set of calibration measurements at a revised set of calibration point locations (Table 5 and Fig. 3). The revised set of calibration point locations moved the outer points from +/- 36 inches (in the x-y horizontal plane) from the geometric center of the calibration space to +/- 18 inches. The vertical placement (z axis) remained unchanged.

Given the measurement data collected for the revised calibration point locations as provided in Table 5, the net count rates for the calibration measurements were determined according to equation 3-1 of the NSC PTVP (UCOR-4443). Based on the WRM3 calibration source data (Table 6), the measured efficiency of the NSC at each of the 11 revised calibration point locations was determined according to equation 4-1 of the NSC PTVP (UCOR-4443). The computed net count rates and measured efficiencies are provided in Table 11, along with the MCNP derived efficiency values for comparison.

Table 10. NSC Count Rates and Efficiencies at the Calibration Point Locations

Location	x (inches)	y (inches)	z (inches)	n_i (c/s) ¹	WF_{234} g U-234 /g U	WF_{235} g U-235 /g U	WF_{238} g U-238/g U	R_{n-234}^2 n/s/g U-234	R_{n-235}^2 n/s/g U-235	R_{n-238}^2 n/s/g U-238	$m_{cal,U235}^3$ (g U-235)	$\mathcal{E}_{i,S,Measured}^4$	$\mathcal{E}_{i,S,MCNP}^6$
1	-36	0	6.25	0.306	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.002283	0.001722
2	-36	0	-6.25	0.236	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.001764	0.001806
3	0	36	6.25	0.247	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.001847	0.001670
4	0	36	-6.25	0.222	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.001660	0.001650
5	36	0	6.25	0.225	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.001681	0.001682
6	36	0	-6.25	0.211	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.001577	0.001726
7	0	-36	6.25	0.178	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.001328	0.001664
8	0	-36	-6.25	0.236	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.001764	0.001669
9	0	0	6.25	0.472	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.003528	0.003864
10	0	0	0	0.467	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.003487	0.003644
11	0	0	-6.25	0.475	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.003549	0.003871
11 ⁵	0	0	-6.25	0.858	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.006413	0.003871
6 ⁵	36	0	-6.25	0.786	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.005873	0.001726

1. net count rate due to the WRM3 calibration source, UCOR-4443: Equation 3-1
2. neutron emission rates of uranium isotopes assuming fully hydrated UO₂F₂, BJC/OR-2862 (U-234), LANL 1991 (U-235, U-238)
3. $m_{cal,U235}$ is the known mass of U-235 in the calibration standard (Appendix A)
4. $\mathcal{E}_{i,S,Measured}$ is the measured efficiency of the NSC with the WRM3 source at the i^{th} calibration point, UCOR-4443: Equation 4-1
5. Initial measurements at these calibration locations performed on 9/12/2013 exhibited significant difference with respect to MCNP derived efficiencies.
6. From Table 7.

Table 11. NSC Count Rates and Efficiencies at the Revised Set of Calibration Point Locations

Location	x (inches)	y (inches)	z (inches)	n_i (c/s) ¹	WF_{234} g U-234 /g U	WF_{235} g U-235 /g U	WF_{238} g U-238/g U	R_{n-234} ² n/s/g U-234	R_{n-235} ² n/s/g U-235	R_{n-238} ² n/s/g U-238	$m_{cal,U235}$ ³ (g U-235)	$\mathcal{E}_{i,S,Measured}$ ⁴	$\mathcal{E}_{i,S,MCNP}$ ⁵
1	-18	0	6.25	0.353	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.002636	0.003033
2	-18	0	-6.25	0.442	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.003300	0.003084
3	0	18	6.25	0.381	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.002843	0.003028
4	0	18	-6.25	0.367	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.002739	0.003038
5	18	0	6.25	0.356	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.002656	0.00298
6	18	0	-6.25	0.419	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.003134	0.003083
7	0	-18	6.25	0.403	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.003009	0.002978
8	0	-18	-6.25	0.372	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.002781	0.002985
9	0	0	6.25	0.553	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.004130	0.003866
10	0	0	0	0.469	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.003507	0.003649
11	0	0	-6.25	0.486	0.003062	0.4552	0.541738	180	0.036	0.0175	105.6	0.003632	0.003857

1. net count rate due to the WRM3 calibration source, UCOR-4443: Equation 3-1
2. neutron emission rates of uranium isotopes assuming fully hydrated UO_2F_2 , BJC/OR-2862 (U-234), LANL 1991 (U-235, U-238)
3. $m_{cal,U235}$ is the known mass of U-235 in the calibration standard (Appendix A)
4. $\mathcal{E}_{i,S,Measured}$ is the measured efficiency of the NSC with the WRM3 source at the i^{th} calibration point, UCOR-4443: Equation 4-1
5. From Table 8.

Table 12 presents a comparison of the measured and MCNP computed efficiencies for all of the calibration measurements. The last 11 entries in Table 12 are the data at the revised set of calibration point locations. Fig. 4 presents a comparison of the percent difference between the efficiency measurements and MCNP computations for the original calibration point locations (+/- 36 inches) and the revised set of calibration point locations (+/- 18 inches). Excluding the initial measurements at locations 6 and 11 in the original set, the average absolute percent difference between the measured and MCNP derived efficiencies at the original calibration point locations is 9.1%, with a standard deviation of 8.8%. The average absolute percent difference between the measured and MCNP derived efficiencies at the revised calibration point locations is 6.8%, with a standard deviation of 3.9%. Overall, the observed differences are more consistent for the revised set of calibration point locations. Furthermore, since the intended use of the measured efficiencies is to derive a normalization to the MCNP determined efficiency for a compressor volute, the revised set of calibration point locations resulted in a more consistent set of data from which to derive this normalization parameter.

Table 12. Comparison of Measured and MCNP derived Efficiencies

Location #	x (inches)	y (inches)	z (inches)	$\epsilon_{i,S,Measured}^1$	$\epsilon_{i,S,MCNP}^2$	% Difference ³
1	-36	0	6.25	0.002283	0.001722	28.015
2	-36	0	-6.25	0.001764	0.001806	-2.353
3	0	36	6.25	0.001847	0.00167	10.065
4	0	36	-6.25	0.00166	0.00165	0.604
5	36	0	6.25	0.001681	0.001682	-0.059
6	36	0	-6.25	0.001577	0.001726	-9.022
7	0	-36	6.25	0.001328	0.001664	-22.460
8	0	-36	-6.25	0.001764	0.001669	5.535
9	0	0	6.25	0.003528	0.003864	-9.091
10	0	0	0	0.003487	0.003644	-4.403
11	0	0	-6.25	0.003549	0.003871	-8.679
11	0	0	-6.25	0.006413	0.003871	49.436
6	36	0	-6.25	0.005873	0.001726	109.146
1	-18	0	6.25	0.002636	0.003033	-14.006
2	-18	0	-6.25	0.0033	0.003084	6.767
3	0	18	6.25	0.002843	0.003028	-6.302
4	0	18	-6.25	0.002739	0.003038	-10.351
5	18	0	6.25	0.002656	0.00298	-11.498
6	18	0	-6.25	0.003134	0.003083	1.641
7	0	-18	6.25	0.003009	0.002978	1.036
8	0	-18	-6.25	0.002781	0.002985	-7.076
9	0	0	6.25	0.00413	0.003866	6.603
10	0	0	0	0.003507	0.003649	-3.969
11	0	0	-6.25	0.003632	0.003857	-6.009

1. Data from Table 10 and Table 11.

2. Data from Table 7 and Table 8.

3.
$$\% \text{ Difference} = 100 \cdot \frac{\epsilon_{i,S,Measured} - \epsilon_{i,S,MCNP}}{\frac{1}{2} \cdot (\epsilon_{i,S,Measured} + \epsilon_{i,S,MCNP})}$$

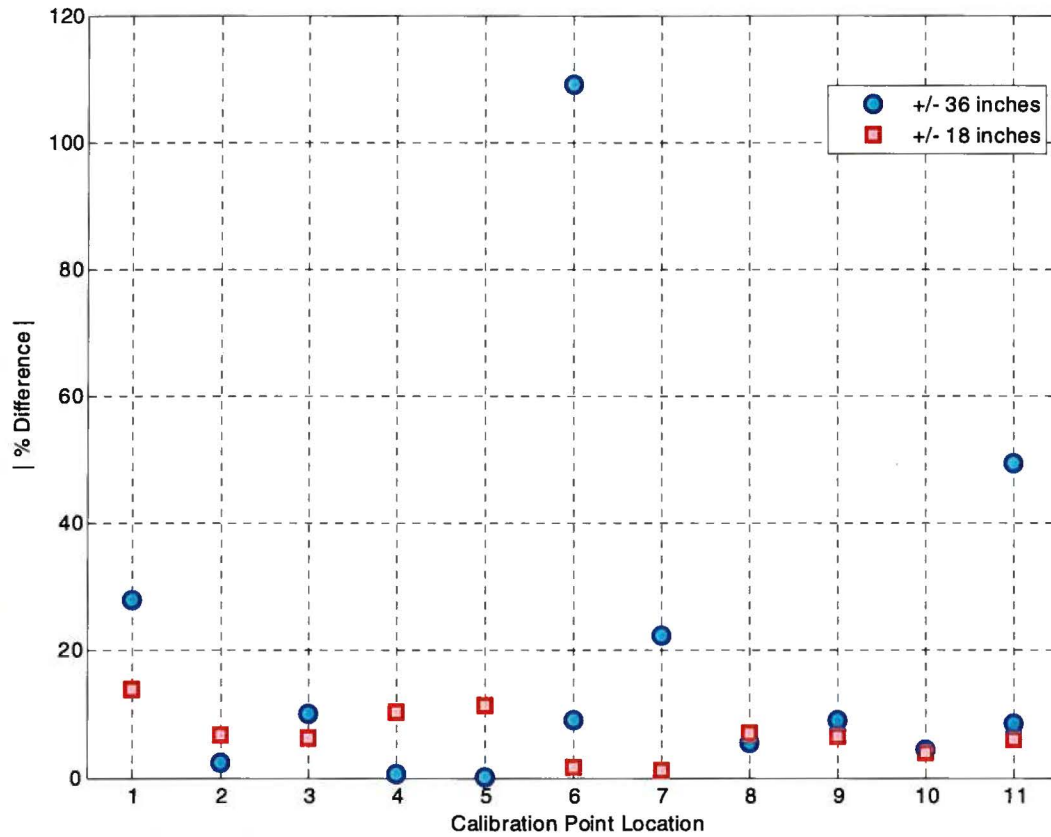


Fig. 4. Comparison of absolute percent difference between the measured efficiencies and MCNP computed efficiencies at the original set (+/- 36 inches) and revised set (+/- 18 inches) of calibration point locations

3.5 AVERAGE EFFICIENCY CALCULATIONS AND NORMALIZATION OF MCNP EFFICIENCY

The measured and MCNP computed efficiencies at the original 11 calibration point locations (+/- 36 inches) are tabulated in Table 13 (excluding the initial measurements at calibration locations 6 and 11 performed on 9/12/2013), and for the revised set of calibration point locations (+/- 18 inches) in Table 14. The average measured efficiency and average MCNP computed efficiency were computed according to the NSC PTV (UCOR-4443) equations 4-2, and 4-3, respectively. The volume weighted average measured and MCNP efficiencies were computed according to the NSC PTV (UCOR-4443) equations 4-4, and 4-5, respectively. The MCNP efficiency was computed according to equation 4-6 of the NSC PTV (UCOR-4443). These calculations were performed on both the original set of calibration point locations (+/- 36 inches) and the revised set of calibration point locations (+/- 18 inches) and are tabulated in Table 15. Because the two sets of calibration point locations are at different coordinates, there resultant averages are will differ; however, the final derived efficiencies from equation 4-6 of the NSC PTV (UCOR-4443), $\varepsilon_{V,NSC}$, show the net impact on the determined efficiency for the NSC. For the original set of calibration point locations (+/- 36 inches), the determined NSC efficiency for a compressor

volute is $\varepsilon_{V,NSC} = 0.5234\%$ and for the revised set of calibration point locations (+/- 18 inches), is $\varepsilon_{V,NSC} = 0.5159\%$.

Table 13. Efficiencies and Volume Fractions for Original Calibration Point Locations

Location	x (inches)	y (inches)	z (inches)	$\varepsilon_{i,S,Measured}^1$	$\varepsilon_{i,S,MCNP}^2$	vf_i^3
1	-36	0	6.25	0.002283	0.001722	0.093276
2	-36	0	-6.25	0.001764	0.001806	0.093276
3	0	36	6.25	0.001847	0.001670	0.093276
4	0	36	-6.25	0.001660	0.001650	0.093276
5	36	0	6.25	0.001681	0.001682	0.093276
6	36	0	-6.25	0.001577	0.001726	0.093276
7	0	-36	6.25	0.001328	0.001664	0.093276
8	0	-36	-6.25	0.001764	0.001669	0.093276
9	0	0	6.25	0.003528	0.003864	0.062000
10	0	0	0	0.003487	0.003644	0.129794
11	0	0	-6.25	0.003549	0.003871	0.062000

1. Data from Table 10.
2. Data from Table 7.
3. NSC PTVP, UCOR-4443, Table 2a.

Table 14. Efficiencies and Volume Fractions for Revised Calibration Point Locations

Location	x (inches)	y (inches)	z (inches)	$\varepsilon_{i,S,Measured}^1$	$\varepsilon_{i,S,MCNP}^2$	vf_i^3
1	-18	0	6.25	0.002636	0.003033	0.116698
2	-18	0	-6.25	0.003300	0.003084	0.116698
3	0	18	6.25	0.002843	0.003028	0.116698
4	0	18	-6.25	0.002739	0.003038	0.116698
5	18	0	6.25	0.002656	0.002980	0.116698
6	18	0	-6.25	0.003134	0.003083	0.116698
7	0	-18	6.25	0.003009	0.002978	0.116698
8	0	-18	-6.25	0.002781	0.002985	0.116698
9	0	0	6.25	0.004130	0.003866	0.015500
10	0	0	0	0.003507	0.003649	0.035419
11	0	0	-6.25	0.003632	0.003857	0.015500

1. Data from Table 11.
2. Data from Table 8.
3. NSC PTVP, UCOR-4443, Table 2b.

Table 15. Summary of NSC Measured and Calculated Efficiencies

Parameter	NSC PTVP Equation # (UCOR-4443)	Original Calibration Locations (Table 13, +/- 36 inches)	Revised Calibration Locations (Table 14, +/- 18 inches)
$\bar{\epsilon}_{S,Measured}$	4-2	0.002224	0.003124
$\bar{\epsilon}_{S,MCNP}$	4-3	0.002270	0.003235
$\bar{\epsilon}_{S,Measured,VW}$	4-4	0.002188	0.002940
$\bar{\epsilon}_{S,MCNP,VW}$	4-5	0.002220	0.003074
$\epsilon_{V,MCNP}$	N/A	0.005341	0.005341
$\epsilon_{V,NSC}$	4-6	0.005234	0.005159

4. Calibration Verification and Performance Test Results

A series of verification and performance test measurements were performed with NSC1 and all data was reported in the NSC PTVR (NDA-13-0622). Table 16 lists the required verification and performance test measurements from Table 5 of the NSC PTVP (UCOR-4443), along with a tally of the number of measurements performed in each case.

Table 16. Summary of Verification and Performance Test Measurement Requirements

Source¹	Configuration	# of Measurements Required	# of Measurements Performed
WRM3	Empty NSC - Center	1	1
WRM7	Empty NSC - Center	1	1
WRM3	Mock Volute - Center	3	3
WRM3	Mock Volute - ¼ Radius	3	3
WRM3	Mock Volute - ½ Radius	3	5
WRM3	Mock Volute - ¾ Radius	3	3
WRM7	Mock Volute - Center	3	3
WRM7	Mock Volute - ¼ Radius	3	5
WRM7	Mock Volute - ½ Radius	3	3
WRM7	Mock Volute - ¾ Radius	3	3

1. Source certificate for WRM3 is provided in Appendix A, source data for WRM7 are available in MCLinc 2008.

Note that measurement control measurements were performed at the frequency required in PROC-DE-0714 and background measurements were performed prior to each verification measurement. If the verification measurement was with a source in the empty NSC then the background measurement was performed with the empty NSC. If the verification measurement was with a source in the mock volute, then the background measurement was performed with the mock volute in the NSC. Prior to beginning the calibration and performance test measurements as described in the NSC PTVP (UCOR-4443), the operational readiness of NSC1 was verified according to PROC-DE-0714.

The NSC PTVP (NDA-13-0622) includes data for 5 replicate measurements of the mock volute with WRM3 placed at ½ the radius of the volute. In addition, two measurements were performed with WRM7 at ¼ radius in the mock volute where the pallet and mock volute assembly were loaded onto the NSC1 platform in the reverse direction (9/19/2013). All other verification and performance test measurements were performed as required in the NSC PTVP (UCOR-4443).

The quantitative U-235 mass determination as prescribed in equation 4-7 and 4-8 of the NSC PTVP (UCOR-4443) are written in a generic form to include the weight fraction and neutron emission rate for U-234, U-235, and U-238. The uranium form and its U-235 enrichment are not assumed to be accurately known during the operation of the NSC. The specific form of uranium has a significant impact on the neutron emission rate of the holdup material, primarily due to the relative amount of fluorine in the material. The assumed material form is fully hydrated UO_2F_2 , and all measured neutrons are assumed to be due to the alpha decay of U-234 inducing (α, n) reactions with fluorine at a rate of $R_{n-234} = 180 \text{ n/s/g}$ U-234; accordingly, $R_{n-235} = R_{n-238} = 0$. Based on these assumptions, equations 4-7 and 4-8 of the PTVP can be reduced to the following forms:

$$m_{U-235,S} = \frac{\left(\frac{WF_{235}}{WF_{234}} \right) \cdot n_i}{\bar{\epsilon}_{S, \text{Measured}, VW} \cdot R_{n-234}} \quad (4-1)$$

$$m_{U-235,V} = \frac{\left(\frac{WF_{235}}{WF_{234}} \right) \cdot r_i}{\epsilon_{V, NSC} \cdot R_{n-234}} \quad (4-2)$$

Equations 4-1 and 4-2 provide the quantitative U-235 mass estimates in g U-235 for the empty NSC and for compressor volute measurements, respectively.

Calibrating with a hydrated UO_2F_2 source produces a conservative bias in the quantitative estimate of U-235 if any fraction of the uranium holdup is in a form with higher fluorine content (i.e. UF_4 or UF_6) or if the material is less than fully hydrated. Verification measurements performed during the Uranium Neutron Counting System PTVP were biased 31% high for the WRM4 anhydrous UO_2F_2 source (BJC-OR-3116).

If the U-235 enrichment of uranium material being measured is known, an appropriate fraction of the measured neutrons can be attributed to the presence of U-235 and U-238; however, during field measurements, the U-235 enrichment is not assumed to be accurately known. This again results in a conservative bias in the quantitative estimate of U-235.

The U-235/U-234 parameter does need to be specified, and this is a function of U-235 enrichment. The method for determination for the U-235/U-234 ratio is to calculate the ratio based on the average U-235 enrichment over the life of the cascade from the building-unit of origin for the specified volute. The

method of calculation, given a U-235 enrichment, is specified in BJC/OR-2862. If the origin is unknown, then the most conservative (lowest) U-235 enrichment should be applied. This conservatism in applying a U-235/U-234 ratio (when the origin is unknown) results in a maximum of ~3% positive bias over the U-235 enrichment range from 0.4% to 20% (based on method of calculation defined in BJC/OR-2862).

4.1 Verification Measurements – Bare Source

The verification measurements with a known source placed in the center of the NSC were performed on 9/14/2013 and are reported in the NSC PTVR (NDA-13-0622). The measurement data are provided in Table 17 and the quantitative results are in

Table 18. According to the NSC PTVP (UCOR-4443) equation 4-7, and its simplified form in this document (equation 4-1), the efficiency to apply to source measurements in the empty NSC is the volume weighted average measured efficiency. The approach for U-235 mass quantification in the NSC PTVP (UCOR-4443) is analogous to that derived for the UNCS. The UNCS is designed as a 4π counting system with a flat efficiency profile across its counting volume, in which case a volume weighted average efficiency can be appropriately applied for a source placed within the UNCS chamber. The NSC is not a 4π counting system, and the efficiency of the system is known to vary by a factor of ~2.5 from its center to the outer edge of the volume of the NSC calibration space. Computing the quantitative U-235 for the WRM3 and WRM7 sources using the volume weighted average efficiency yields a 67.2% and 68.9% bias for the original set of calibration point locations, and a 24.4% and 25.7% bias for the revised set of calibration point locations. This high bias is due to the volume weighted average efficiency being reduced by the lower efficiencies away from the centerline of the NSC. Evaluating these data with the measured efficiency at the center of the NSC (calibration location 10) yields bias values of 4.9% (WRM3, +/- 36), 4.3% (WRM3, +/- 18), 6.0% (WRM7, +/- 36) and 5.4% (WRM7, +/- 18).

Table 17. Verification Measurements with Empty NSC

Source	x (inches)	y (inches)	z (inches)	Date	Upper Slab				Lower Slab			
					F_1^1 (counts)	t_{F_1} (s)	B_1^3 (counts)	t_{B_1} (s)	F_2^2 (counts)	t_{F_2} (s)	B_2^4 (counts)	t_{B_2} (s)
WRM3	0	0	0	9/14/13	3340	3600	2430	3600	3610	3600	2840	3600
WRM7	0	0	0	9/14/13	4500	3600	2500	3600	4860	3600	2770	3600

1. F_1 (c) is the total neutron counts from the upper slab detector (K333172) collected within time t_{F_1} (s), with the WRM3 source at the specified calibration point.
2. F_2 (c) is the total neutron counts from the lower slab detector (K333772) collected within time t_{F_2} (s), with the WRM3 source at the specified calibration point.
3. B_1 (c) is the total background neutron counts from the upper slab detector (K333172) collected within time t_{B_1} (s), without the surrogate volute in place.
4. B_2 (c) is the total background neutron counts from the lower slab detector (K333772) collected within time t_{B_2} (s), without the surrogate volute in place.

Table 18. Quantitative Results and Bias for Verification Measurements with Empty NSC

Description	Date	n_i (c/s) ¹	WF_{235}/WF_{234} ²	Efficiency Description ⁴	ϵ	$m_{U-235,S}$ ³ (g U-235)	$m_{U-235,Known}$ ² (g U-235)	Bias (%)
WRM3	9/14/13	0.466667	149	$\bar{\epsilon}_{S,Measured,VW}$, (+/- 36)	0.002188	176.53	105.6	67.2
				ϵ_{10} , (+/- 36)	0.003487	110.80	105.6	4.9
				$\bar{\epsilon}_{S,Measured,VW}$, (+/- 18)	0.002940	131.39	105.6	24.4
				ϵ_{10} , (+/- 18)	0.003507	110.14	105.6	4.3
WRM7	9/14/13	1.136111	145	$\bar{\epsilon}_{S,Measured,VW}$, (+/- 36)	0.002188	418.23	247.6	68.9
				ϵ_{10} , (+/- 36)	0.003487	262.50	247.6	6.0
				$\bar{\epsilon}_{S,Measured,VW}$, (+/- 18)	0.002940	311.29	247.6	25.7
				ϵ_{10} , (+/- 18)	0.003507	260.94	247.6	5.4

1. net count rate due to the WRM3 calibration source, NSC PTVP (UCOR-4443) Equation 3-1.
2. see appendix A for WRM3 and MCLinc 2008 for WRM7.
3. Equation 4-1.
4. (+/- 36) efficiencies derived from original set of calibration point locations, (+/- 18) efficiencies derived from revised set of calibration point locations, ϵ_{10} is the measured efficiency at calibration point location 10 (the geometric center of the NSC).

4.2 Verification Measurements – Source in Mock Volute

The verification measurements with a known source placed at prescribed locations (see Table 16) within the mock volute were performed from 9/16/2013 to 9/26/2013 and are reported in the NSC PTVR (NDA-13-0622). The measurement data are provided in Table 19 and the quantitative results are in Table 20. According to the NSC PTVR (UCOR-4443) equation 4-8, and its simplified form in this document (equation 4-2), the quantitative U-235 value was computed for each verification measurement. From this point forward, all efficiencies used will be based on the data collected at the revised set of calibration point locations (+/- 18). Thus, the NSC efficiency for all of the verification measurements performed with the mock volute is 0.5159% (see Table 15).

The bias of each verification measurement is provided in Table 20, along with the average bias for each set of 3 replicate measurements. With a source placed in the center of the mock volute, the total average bias is -7.67%, with a source at $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of the radius (28.75 inches) in the mock volute the total average bias results are -20.0%, -55.3%, and -53.9%, respectively. The total average bias over all verification measurements is -31%.

The area in the volute behind the impeller is a stagnant area for UF_6 . The flow into the compressor comes in through the inlet and is then compressed and exits through the discharge. Any wet air inleakage to this area that produced solid uranium materials would most likely be quickly carried through the piping to the nearest converter where barrier plugging would result. Thus deposits in the volute on the front side of the impeller where UF_6 flow is rapid are unlikely.

The seal is located in center of the volute behind the impeller and seal failure is the most likely initiator of wet air inleakage in the cascade. Couple the likelihood of wet air inleakage from a failed seal with the stagnant UF_6 behind the impeller, and any solid uranium materials formed from the seal failure have no motive force to carry them away from this area, and the deposit will build up. Deposits will most likely be in the seal area of the volute and on the back side of the impeller inside the BOP ring.

Failure of an expansion joint in the compressor suction piping will result in a more evenly distributed (because of the presence of UF_6 flow) deposit on the front of the impeller and around the inside of the volute. The seal was the most failure prone piece of process equipment in the gaseous diffusion cascade with an annual failure rate approaching 10% while expansion joints failed at a rate of less than 1%.

The NSC efficiency was determined based on hydrated UO_2F_2 in the seal cavity of the compressor volute. This configuration is most similar to the verification measurements with the source placed in the center of the volute. The verification measurements at $\frac{1}{4}$ of the radius of the mock volute represent the response at the outer radius of the seal cavity. The $\frac{1}{2}$ radius and $\frac{3}{4}$ radius verification measurements represent configurations which are not expected conditions for the compressor volutes that will be measured with the NSC. Evaluating the total average bias over the center and $\frac{1}{4}$ radius measurements only (excluding data from 9/16, due to the improper loading of the pallet volute assembly) results in -13.9%.

Table 19. Verification Measurements with Mock Volute

Source	Position	Date	Upper Slab				Lower Slab			
			V_1^1 (counts)	t_{V_1} (s)	C_1^3 (counts)	t_{C_1} (s)	V_2^2 (counts)	t_{V_2} (s)	C_2^4 (counts)	t_{C_2} (s)
WRM3	Center	9/23/13	3660	3600	2720	3600	3930	3600	2850	3600
WRM3	Center	9/23/13	3860	3600	2610	3600	4020	3600	2780	3600
WRM3	Center	9/23/13	3890	3600	2710	3600	3950	3600	2820	3600
WRM3	1/4 Radius	9/27/13	3650	3600	2660	3600	3770	3600	2800	3600
WRM3	1/4 Radius	9/27/13	3590	3600	2620	3600	3710	3600	2790	3600
WRM3	1/4 Radius	9/27/13	3620	3600	2630	3600	3700	3600	2740	3600
WRM3	1/2 Radius	9/24/13	3450	3600	2810	3600	3380	3600	2750	3600
WRM3	1/2 Radius	9/24/13	3420	3600	2690	3600	3430	3600	2790	3600
WRM3	1/2 Radius	9/24/13	3650	3600	2730	3600	3590	3600	2870	3600
WRM3	1/2 Radius	9/25/13	3490	3600	2750	3600	3480	3600	2860	3600
WRM3	1/2 Radius	9/25/13	3490	3600	2770	3600	3470	3600	2850	3600
WRM3	3/4 Radius	9/26/13	3230	3600	2760	3600	3310	3600	2800	3600
WRM3	3/4 Radius	9/26/13	3300	3600	2670	3600	3400	3600	2770	3600
WRM3	3/4 Radius	9/26/13	3330	3600	2730	3600	3300	3600	2760	3600
WRM7	Center	9/17/13	4780	3600	2670	3600	5380	3600	2640	3600
WRM7	Center	9/17/13	5060	3600	2620	3600	5440	3600	2670	3600
WRM7	Center	9/17/13	5050	3600	2630	3600	5560	3600	2850	3600
WRM7	1/4 Radius	9/20/13	4810	3600	2700	3600	5300	3600	2800	3600
WRM7	1/4 Radius	9/20/13	4670	3600	2740	3600	5050	3600	2750	3600
WRM7	1/4 Radius	9/20/13	4880	3600	2840	3600	5240	3600	2710	3600
WRM7	1/4 Radius	9/16/13	4940	3600	2680	3600	5010	3600	2700	3600
WRM7	1/4 Radius	9/16/13	4710	3600	2690	3600	5070	3600	2740	3600
WRM7	1/2 Radius	9/18/13	4420	3600	2540	3600	3990	3600	2560	3600
WRM7	1/2 Radius	9/18/13	4340	3600	2570	3600	3950	3600	2800	3600
WRM7	1/2 Radius	9/18/13	4520	3600	2500	3600	4350	3600	2700	3600
WRM7	3/4 Radius	9/19/13	4000	3600	2570	3600	3750	3600	2690	3600
WRM7	3/4 Radius	9/19/13	4180	3600	2640	3600	3800	3600	2740	3600
WRM7	3/4 Radius	9/19/13	4160	3600	2730	3600	3950	3600	2810	3600

1. V_1 (c) is the total neutron count from the upper slab detector (K333172) collected within time t_{V_1} (s), with the WRM3 source at the specified position in the mock volute.
2. V_2 (c) is the total neutron count from the lower slab detector (K333772) collected within time t_{V_2} (s), with the WRM3 source at the specified position in the mock volute.
3. C_1 (c) is the total background neutron count from the upper slab detector (K333172) collected within time t_{C_1} (s), with the mock volute in the NSC.
4. C_2 (c) is the total background neutron count from the lower slab detector (K333772) collected within time t_{C_2} (s), with the mock volute in the NSC.

Table 20. Quantitative Results and Bias for Verification Measurements with Mock Volute

Source	Position	Date	r_i (c/s) ¹	WF_{235} / WF_{234} ³	$\mathcal{E}_{V,NSC}$	$m_{U\ 235,V}$ ⁴ (g U-235)	$m_{U\ 235,Known}$ ³ (g U-235)	Bias (%)	$\overline{m}_{U\ 235,V}$ (g U-235)	Average Bias (%)
WRM3	Center	9/23/13	0.561111	149	0.005159	90.04	105.6	-14.7	101.3	-4.0
WRM3	Center	9/23/13	0.691667	149	0.005159	110.99	105.6	5.1		
WRM3	Center	9/23/13	0.641667	149	0.005159	102.96	105.6	-2.5		
WRM3	1/4 Radius	9/27/13	0.544444	149	0.005159	87.36	105.6	-17.3	86.2	-18.4
WRM3	1/4 Radius	9/27/13	0.525	149	0.005159	84.24	105.6	-20.2		
WRM3	1/4 Radius	9/27/13	0.541667	149	0.005159	86.92	105.6	-17.7		
WRM3	1/2 Radius	9/24/13	0.352778	149	0.005159	56.61	105.6	-46.4	62.2	-41.1
WRM3	1/2 Radius	9/24/13	0.380556	149	0.005159	61.06	105.6	-42.2		
WRM3	1/2 Radius	9/24/13	0.455556	149	0.005159	73.10	105.6	-30.8		
WRM3	1/2 Radius	9/25/13	0.377778	149	0.005159	60.62	105.6	-42.6		
WRM3	1/2 Radius	9/25/13	0.372222	149	0.005159	59.73	105.6	-43.4		
WRM3	3/4 Radius	9/26/13	0.272222	149	0.005159	43.68	105.6	-58.6	50.2	-52.4
WRM3	3/4 Radius	9/26/13	0.35	149	0.005159	56.16	105.6	-46.8		
WRM3	3/4 Radius	9/26/13	0.316667	149	0.005159	50.81	105.6	-51.9		
WRM7	Center	9/17/13	1.347222	145	0.005159	210.37	247.6	-15.0	219.6	-11.3
WRM7	Center	9/17/13	1.447222	145	0.005159	225.99	247.6	-8.7		
WRM7	Center	9/17/13	1.425	145	0.005159	222.52	247.6	-10.1		
WRM7	1/4 Radius	9/20/13	1.280556	145	0.005159	199.96	247.6	-19.2	193.9	-21.7
WRM7	1/4 Radius	9/20/13	1.175	145	0.005159	183.48	247.6	-25.9		
WRM7	1/4 Radius	9/20/13	1.269444	145	0.005159	198.23	247.6	-19.9		
WRM7	1/4 Radius ²	9/16/13	1.269444	145	0.005159	198.23	247.6	-19.9	143.1	-42.2
WRM7	1/4 Radius ²	9/16/13	1.208333	145	0.005159	188.69	247.6	-23.8		
WRM7	1/2 Radius	9/18/13	0.919444	145	0.005159	143.58	247.6	-42.0		
WRM7	1/2 Radius	9/18/13	0.811111	145	0.005159	126.66	247.6	-48.8		
WRM7	1/2 Radius	9/18/13	1.019444	145	0.005159	159.19	247.6	-35.7		
WRM7	3/4 Radius	9/19/13	0.691667	145	0.005159	108.01	247.6	-56.4	110.8	-55.3
WRM7	3/4 Radius	9/19/13	0.722222	145	0.005159	112.78	247.6	-54.5		
WRM7	3/4 Radius	9/19/13	0.713889	145	0.005159	111.48	247.6	-55.0		

1. net count rate for compressor volute measurement, NSC PTVP (UCOR-4443) Equation 3-2.
2. The pallet and volute assembly was loaded onto the NSC platform in the reverse orientation.
3. see appendix A for WRM3 and MCLinc 2008 for WRM7.
4. Equation 4-2.

5. Evaluation of Minimum Detectable Activity and Total Measurement Uncertainty

All calibration measurement data evaluated under this section are from the revised set of calibration point locations (+/- 18). The individual terms in the TMU calculation for the NSC are evaluated in this section along with the background variability and determination of the MDA for the verification measurements.

5.1 NSC COUNTING STATISTICS AND UNCERTAINTY

The uncertainties due to counting statistics for measurements with a source in the empty NSC were computed according to a modified form of the NSC PTVP equation (5-1). The modified form of the counting statistics uncertainty equation was implemented due to the planned use of existing UNCS software for application to the NSC. Within the existing UNCS software, a measurement is characterized by a single total count and counting time. The modified form of the counting statistics calculation is provided as equation 5-1 below:

$$\sigma_n = \sqrt{\frac{F}{t_F^2} + \frac{B}{t_B^2}} \quad (5-1)$$

Where $F = F_1 + F_2$ is the sum of the foreground counts from the upper and lower detectors collected over a time period of t_F and $B = B_1 + B_2$ is the sum of the background counts from the upper and lower detectors collected over a time period t_B . The configuration of the UNCS software requires that the input count time be the time over which the input total counts were collected; thus, for the NSC PTVP measurements, $t_F = t_B = 3600$ seconds. The counting statistics uncertainty calculations according to equation 5-1 are provided in Table 21.

Table 21. Counting Statistics for Measurements in the Empty NSC

Description	F (counts)	t_F (s)	B (counts)	t_B (s)	n_i (c/s) ¹	σ_{n_i} ⁽²⁾	% $RSD_{CS,S}$
Cal. Pt 1 (WRM3)	6400	3600	5130	3600	0.352778	0.029827	8.45
Cal. Pt 2 (WRM3)	6700	3600	5110	3600	0.441667	0.030187	6.83
Cal. Pt 3 (WRM3)	6380	3600	5010	3600	0.380556	0.029646	7.79
Cal. Pt 4 (WRM3)	6280	3600	4960	3600	0.366667	0.029450	8.03
Cal. Pt 5 (WRM3)	6350	3600	5070	3600	0.355556	0.029685	8.35
Cal. Pt 6 (WRM3)	6480	3600	4970	3600	0.419444	0.029724	7.09
Cal. Pt 7 (WRM3)	6460	3600	5010	3600	0.402778	0.029749	7.39
Cal. Pt 8 (WRM3)	6370	3600	5030	3600	0.372222	0.029659	7.97
Cal. Pt 9 (WRM3)	7010	3600	5020	3600	0.552778	0.030467	5.51
Cal. Pt 10 (WRM3)	6780	3600	5090	3600	0.469444	0.030264	6.45
Cal. Pt 11 (WRM3)	6960	3600	5210	3600	0.486111	0.030644	6.30
WRM3 at (0,0,0)	6950	3600	5270	3600	0.466667	0.030707	6.58
WRM7 at (0,0,0)	9360	3600	5270	3600	1.136111	0.033598	2.96

1. net count rate due to the WRM3 calibration source, NSC PTVP UCOR-4443: Equation 3-1.
2. uncertainty due to counting statistics for the measurement of a bare WRM source, Equation 5-1.
3. relative standard deviation of the counting statistics uncertainty term, NSC PTVP Equation 5-3.

The uncertainties due to counting statistics for measurements with WRM sources in the mock volute in the NSC were computed according to a modified form of the NSC PTVP equation (5-2). The modified form is shown in equation 5-2 below.

$$\sigma_r = \sqrt{\frac{V}{t_v^2} + \frac{C}{t_c^2}} \quad (5-2)$$

Where $V = V_1 + V_2$ is the sum of the foreground counts from the upper and lower detectors collected over a time period of t_v and $C = C_1 + C_2$ is the sum of the background counts from the upper and lower detectors collected over a time period t_c .

The counting statistics uncertainty calculations for the verification measurements with the WRM3 source in the mock volute according to equation 5-2 are provided in Table 23.

Table 22. Counting Statistics for Measurements of Mock Volute in the NSC

Date	Source	Position	V (counts)	t_V (s)	C (counts)	t_C (s)	r_i (c/s) ¹	σ_{r_i} ⁽²⁾	%RSD _{CS,V}
9/23/13	WRM3	Center	7590	3600	5570	3600	0.561111	0.031866	5.68
9/23/13	WRM3	Center	7880	3600	5390	3600	0.691667	0.031999	4.63
9/23/13	WRM3	Center	7840	3600	5530	3600	0.641667	0.032119	5.01
9/27/13	WRM3	1/4 Radius	7420	3600	5460	3600	0.544444	0.031525	5.79
9/27/13	WRM3	1/4 Radius	7300	3600	5410	3600	0.525	0.031316	5.97
9/27/13	WRM3	1/4 Radius	7320	3600	5370	3600	0.541667	0.031292	5.78
9/24/13	WRM3	1/2 Radius	6830	3600	5560	3600	0.352778	0.03092	8.76
9/24/13	WRM3	1/2 Radius	6850	3600	5480	3600	0.380556	0.030845	8.11
9/24/13	WRM3	1/2 Radius	7240	3600	5600	3600	0.455556	0.031476	6.91
9/25/13	WRM3	1/2 Radius	6970	3600	5610	3600	0.377778	0.031156	8.25
9/25/13	WRM3	1/2 Radius	6960	3600	5620	3600	0.372222	0.031156	8.37
9/26/13	WRM3	3/4 Radius	6540	3600	5560	3600	0.272222	0.030556	11.2
9/26/13	WRM3	3/4 Radius	6700	3600	5440	3600	0.35	0.030606	8.74
9/26/13	WRM3	3/4 Radius	6630	3600	5490	3600	0.316667	0.030581	9.66
9/17/13	WRM7	Center	10160	3600	5310	3600	1.347222	0.034550	2.56
9/17/13	WRM7	Center	10500	3600	5290	3600	1.447222	0.034905	2.41
9/17/13	WRM7	Center	10610	3600	5480	3600	1.425	0.035235	2.47
9/20/13	WRM7	1/4 Radius	10110	3600	5500	3600	1.280556	0.034706	2.71
9/20/13	WRM7	1/4 Radius	9720	3600	5490	3600	1.175	0.034258	2.92
9/20/13	WRM7	1/4 Radius	10120	3600	5550	3600	1.269444	0.034772	2.74
9/16/13	WRM7	1/4 Radius	9950	3600	5380	3600	1.269444	0.034393	2.71
9/16/13	WRM7	1/4 Radius	9780	3600	5430	3600	1.208333	0.034258	2.84
9/18/13	WRM7	1/2 Radius	8410	3600	5100	3600	0.919444	0.032287	3.51
9/18/13	WRM7	1/2 Radius	8290	3600	5370	3600	0.811111	0.032466	4.00
9/18/13	WRM7	1/2 Radius	8870	3600	5200	3600	1.019444	0.032949	3.23
9/19/13	WRM7	3/4 Radius	7750	3600	5260	3600	0.691667	0.031684	4.58
9/19/13	WRM7	3/4 Radius	7980	3600	5380	3600	0.722222	0.032107	4.45
9/19/13	WRM7	3/4 Radius	8110	3600	5540	3600	0.713889	0.032454	4.55

1. net count rate for volute measurement, NSC PTPV UCOR-4443: Equation 3-2.
2. uncertainty due to counting statistics for the measurement of a volute, Equation 5-2.
3. relative standard deviation of the counting statistics uncertainty term, NSC PTPV Equation 5-4.

5.2 NSC CALIBRATION COUNTING STATISTICS AND UNCERTAINTY

The calibration counting statistics uncertainty calculations according to the NSC PTPV (UCOR-4443) equation 5-7 with the σ_n term being determined from equation 5-1 are provided in Table 23.

Table 23. Calibration Counting Data and Uncertainty Computations (Empty Calibration Space)

Location	F (counts)	t_F (s)	B (counts)	t_B (s)	σ_{n_i}	vf_i	$\sigma_{n_i}^2 \cdot vf_i^2$
1	6400	3600	5130	3600	0.029827	0.11670	0.0000121156997329
2	6700	3600	5110	3600	0.030187	0.11670	0.0000124099231435
3	6380	3600	5010	3600	0.029646	0.11670	0.0000119685880275
4	6280	3600	4960	3600	0.029450	0.11670	0.0000118109683432
5	6350	3600	5070	3600	0.029685	0.11670	0.0000120001119644
6	6480	3600	4970	3600	0.029724	0.11670	0.0000120316359012
7	6460	3600	5010	3600	0.029749	0.11670	0.0000120526518591
8	6370	3600	5030	3600	0.029659	0.11670	0.0000119790960065
9	7010	3600	5020	3600	0.030467	0.01550	0.0000002230098380
10	6780	3600	5090	3600	0.030264	0.03542	0.0000011489842344
11	6960	3600	5210	3600	0.030644	0.01550	0.0000002256051312
$\sum_{i=1}^m \sigma_{n_i}^2 \cdot vf_i^2$							0.000097966
$\frac{WF_{235}}{(WF_{234} \cdot R_{n-234} + WF_{235} \cdot R_{n-235} + WF_{238} \cdot R_{n-238})}$							0.788952949
$m_{cal,U\ 235}$ g U-235							105.6
$\sigma_{CCS,S}^2$ (NSC PTVP, UCOR-4443, Equation 5-7), with σ_{n_i} determined from equation 5-1							5.4683E-09
$\sigma_{CCS,S}$							7.3948E-05
$\bar{\epsilon}_{S,Measured,VW}$							0.002940
$\%RSD_{CCS,S}$ (NSC PTVP, UCOR-4443, Equation 5-9)							2.52

The calibration counting statistics for compressor volute measurements are based on the MCNP generated data. The source applied in MCNP to determine the NSC efficiency for volute measurements is defined in Table 24. The uncertainty due to calibration counting statistics for compressor volutes is calculated according to the NSC PTVP (UCOR-4443) equation 5-8.

Table 24. 1000 g U-235 Source Definition for MCNP - Volute

Source Parameter	Value
g U-235/ g U	0.2
g U-235/ g U-234 ¹	153.35
g U	5000
g U-234	6.52
g U-235	1000
g U-238	3993.48
g H	84.69
g O	1344.11
g F	798.25
g Total	7227.05
WF234	0.0013042
WF235	0.2
WF238	0.7986958
Total (n/s)	1279.7

1. BJC/OR-2862

Table 25. MCNP Counting Data and Uncertainty Computations (Compressor Volute)

$\frac{WF_{235}}{(WF_{234} \cdot R_{n-234} + WF_{235} \cdot R_{n-235} + WF_{238} \cdot R_{n-238})}$	0.78147
$m_{cal,U\ 235}$ g U-235	1000
V_{MCNP} (counts)	24605
$t_{V,MCNP}$ (seconds)	3600
$\sigma_{CCS,V}^2$ (PTVP Equation 5-8)	1.159E-09
$\sigma_{CCS,V}$	3.405E-05
$\mathcal{E}_{V,MCNP}$	0.005341
$\%RSD_{CCS,V}$ (PTVP Equation 5-10)	0.638

5.3 CALIBRATION SOURCE MASS UNCERTAINTY

The uncertainty of the WRM3 calibration source U-235 mass value is +/- 5% (MCLinc 2008); thus, the calibration source mass relative standard deviation (NSC PTVP, UCOR-4443, equation 5-13):

$$\%RSD_{CM} = 5$$

5.4 SOURCE LOCATION UNCERTAINTY

The methodology for determining source location uncertainty for the empty calibration space was defined in the NSC PTVP (UCOR-4443) equations 5-16 through 5-19. Table 26 demonstrates these calculations. The determination of $\sigma_{SL,S}$ from the NSC PTVP (UCOR-4443) equation 5-18 implements the conservative assumption that $\sigma_{CCS,S}^2=0$, which results in a negligible impact due to $\sigma_{\epsilon,S}^2 \gg \sigma_{CCS,S}^2$. This method of calculation mimics that performed in the UNCS software and consequently the planned NSC software. Without this modification the $\%RSD_{SL,S}$ is 17.28% as opposed to the 17.46% result as shown in Table 26.

Table 26. Measured Efficiency Data and Source Location Uncertainty Computations (Empty Calibration Space)

Calibration Point Location	$\epsilon_{i,S,Measured}$	$\epsilon_{i,S,Measured} - \bar{\epsilon}_{S,Measured,VW}$	$[\epsilon_{i,S,Measured} - \bar{\epsilon}_{S,Measured,VW}]^2$
1	0.002636	-3.0439E-04	9.2655E-08
2	0.003300	3.5971E-04	1.2939E-07
3	0.002843	-9.6861E-05	9.3820E-09
4	0.002739	-2.0063E-04	4.0251E-08
5	0.002656	-2.8364E-04	8.0451E-08
6	0.003134	1.9368E-04	3.7513E-08
7	0.003009	6.9165E-05	4.7838E-09
8	0.002781	-1.5912E-04	2.5319E-08
9	0.004130	1.1898E-03	1.4157E-06
10	0.003507	5.6724E-04	3.2176E-07
11	0.003632	6.9176E-04	4.7853E-07
$\bar{\epsilon}_{S,Measured,VW}$			0.002940
m			11
$\sum_{i=1}^m [\epsilon_{i,S,Measured} - \bar{\epsilon}_{S,Measured,VW}]^2$			2.6358E-06
$\sigma_{\epsilon,S}^2$ ¹			2.63575E-07
$\sigma_{CCS,S}^2$ ⁽²⁾			5.46828E-09
$\sigma_{SL,S}$ ⁽³⁾			5.1340E-04
$\%RSD_{SL,S}$ ⁴			17.46

1. NSC PTVP (UCOR-4443) Equation 5-17

2. see Table 23.

3. calculated according to the NSC PTVP (UCOR-4443), Equation 5-18, where $\sigma_{CCS,S}^2 = 0$.

4. NSC PTVP (UCOR-4443), Equation 5-19.

To evaluate the source location uncertainty for measurement of compressor volutes in the NSC a set of MCNP models were run with a point source placed within the central plane of the volute on the NSC platform. Each model included the volute itself and its containing wood pallet. The volute area along its central plane was divided into a one inch grid and an efficiency value determined for placing a point source at each of these locations. The resultant number of point source models was 2450, based on the

volute geometry for a size 92 compressor (DWG MIE702500A718). The point source was defined as shown in Table 27. Fig. 5 shows the grid of point source locations, and Fig. 6 shows the resultant efficiency values determined from the MCNP runs. The full set of data is available in the NSC PTVR (NDA-13-0622).

Table 27. 200 g U-235 Point Source Definition for MCNP

Source Parameter	Value
g U-235/ g U	0.03
g U-235/ g U-234 ¹	156.56
g U	6667
g U-234	1.28
g U-235	200
g U-238	6465
g H	113
g O	1792
g F	1064
g Total	9636
U-234 (n/s) ²	230.0
U-235 (n/s) ²	7.2
U-238 (n/s) ²	113.1
Total (n/s)	350.3

1. BJC/OR-2862

2. Based on n/s/g U-234 in fully hydrated UO₂F₂ from BJC/OR-2862

3. Based on n/s/g U-235 and n/s/g U-238 for UO₂F₂ from LANL 1991

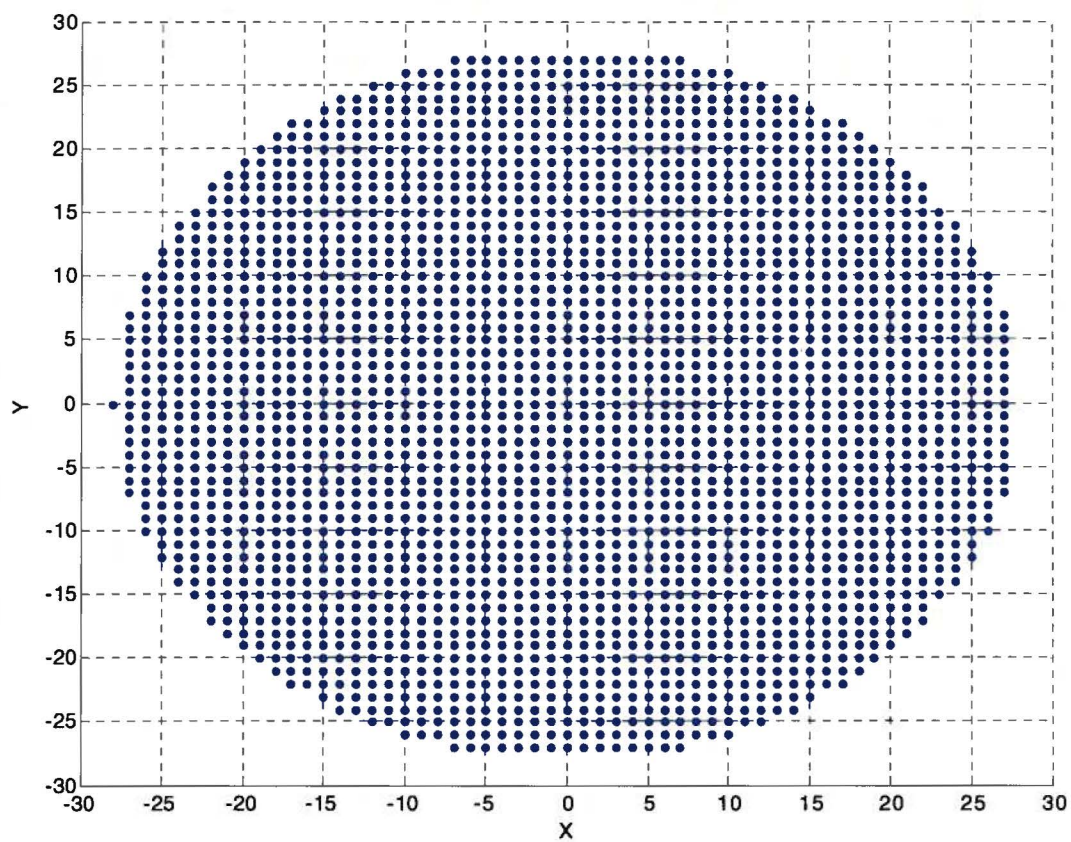


Fig. 5 Grid of point locations for MCNP point source models within the compressor volute (X and Y values are in inches and referenced from the center of the volute in the X-Y plane)

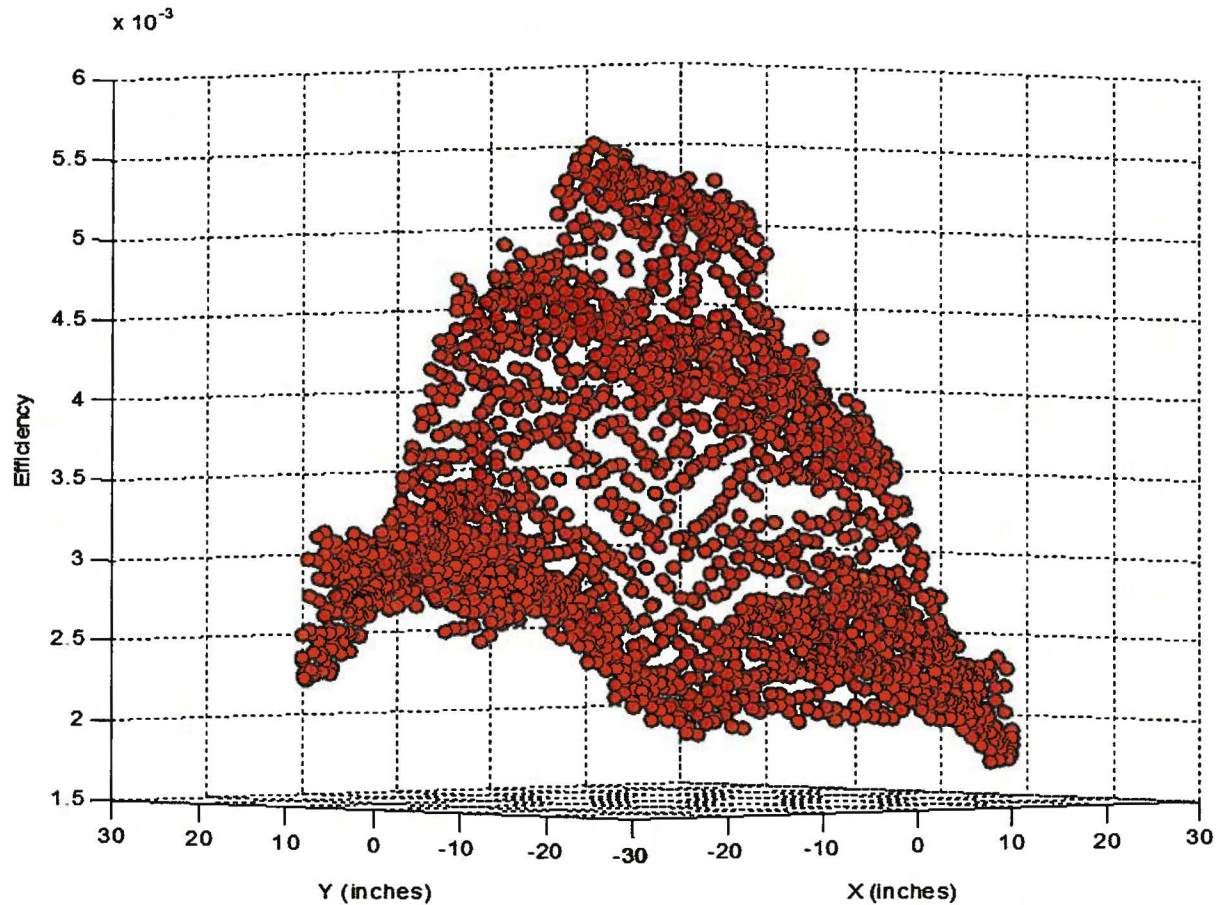


Fig. 6 MCNP efficiencies across the central plane of a compressor volute

The minimum efficiency obtained was 0.176% and the maximum was 0.562%. The average efficiency was 0.334% with a standard deviation of 0.0936%, resulting in a relative standard deviation of 28%. Based on these efficiency data the following process was run to further evaluate the source location uncertainty.

1. Load the MCNP efficiency data file
2. Define a number of point sources (NP) to select from the population of 2450.
3. Randomly select NP efficiency points from the population of 2450 without replacement.
4. Calculate the average of the randomly selected NP efficiency values.
5. Replace all efficiency points back into the population.
6. Repeat steps 3 and 4 N times (N=10,000).
7. Repeat steps 2 through 6 for all desired numbers of point sources (NP)

The MATLAB code used to implement this process is provided in Appendix B. This process was run for NP from 1 to 750. For each value of NP (number of random points to select from the population of 2450), N=10,000 runs were performed. The full set of N average values for each value of NP are plotted in Fig. 7. As expected, the variance over the N runs decreases as the number of random points over which the efficiencies are determined increases.

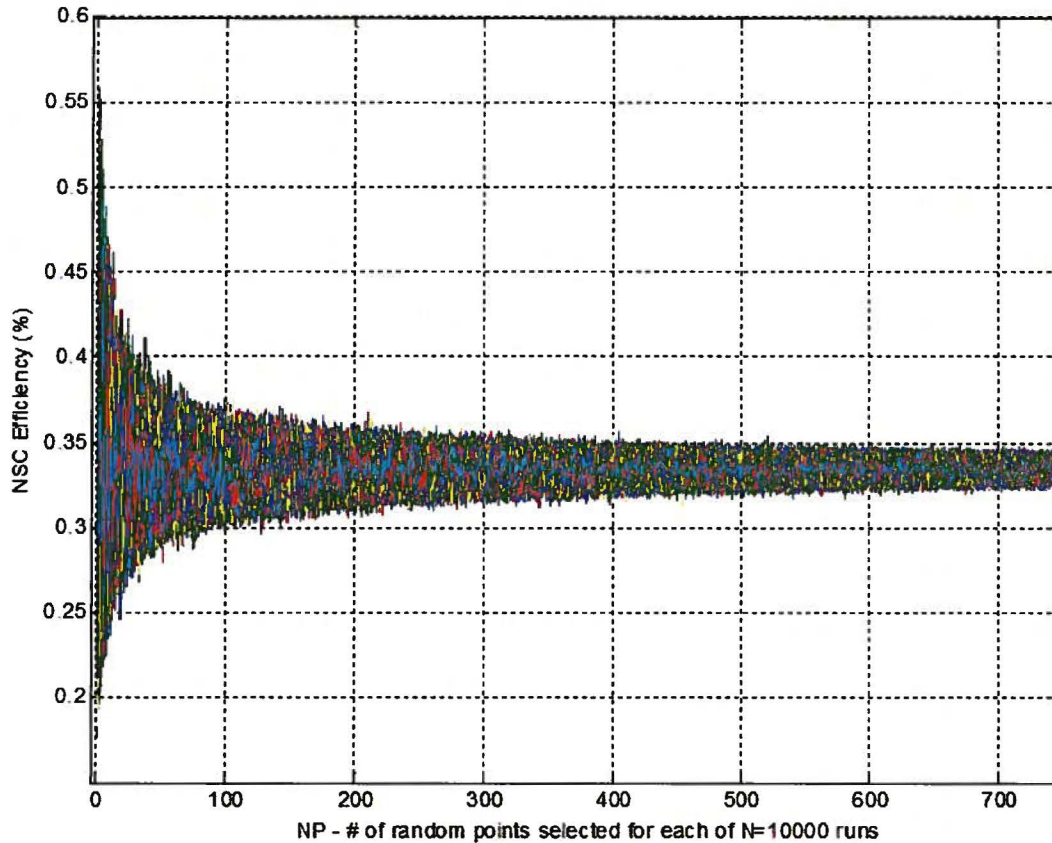


Fig. 7. Average MCNP efficiency values determined for source location uncertainty evaluation.

The relative standard deviation (RSD) of the data presented in Fig. 7 can be computed for each value of NP. The set of RSD values obtained are presented in Fig. 8. The source location uncertainty for the compressor volute measurements can be approximated by the RSD for a specific value of NP. At its maximum, the RSD is 28% representing an appropriate measure of source location uncertainty for a compressor volute if the source is a point at any location within the volute. It is not a practical assumption that the UO_2F_2 holdup in a compressor volute is in the form of a point source; however, the appropriate specification for $\text{NP} > 1$ is subject to assumptions regarding the distribution of the holdup source. Fig. 9 provides a zoom view of Fig. 8, from which it can be seen that given a set of efficiencies derived by setting $\text{NP}=4$, the RSD is less than 15%. That is, if one assumes that the holdup material is randomly distributed at 4 point source locations, the RSD is less than 15%. An improved approximation to expected physical deposit distribution would limit the NP points to an area in the vicinity of the first random point, that area being defined based on the assumed area for a holdup deposit. With the minimum amount of assumption, the most conservative approach can be applied resulting in a source location uncertainty for compressor volute measurements of 28%.

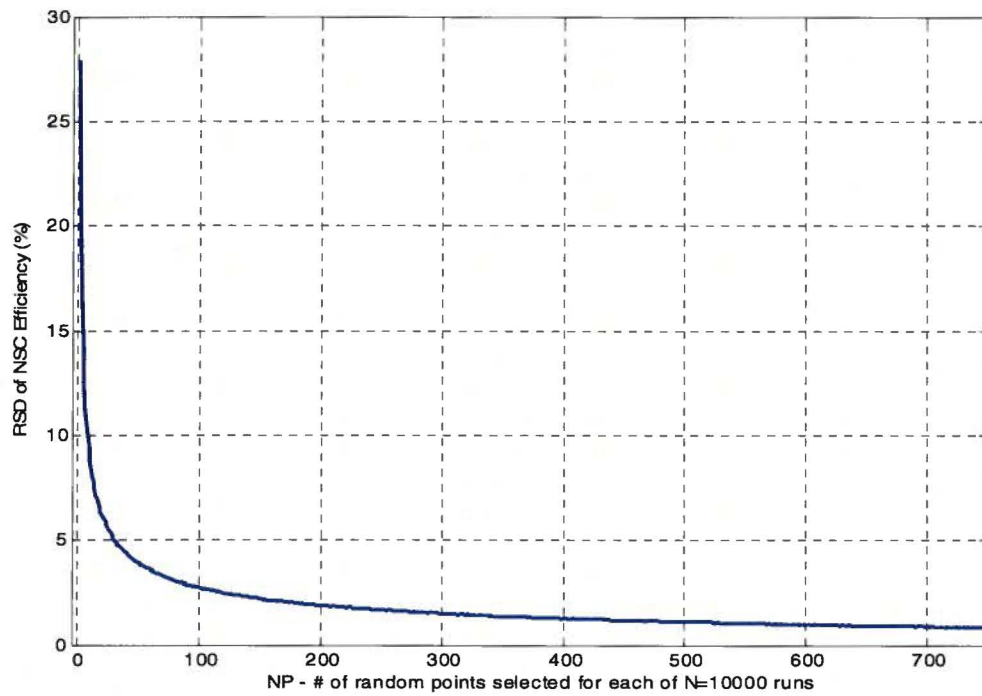


Fig. 8. Relative Standard Deviations computed over the N=10,000 runs at each value of NP.

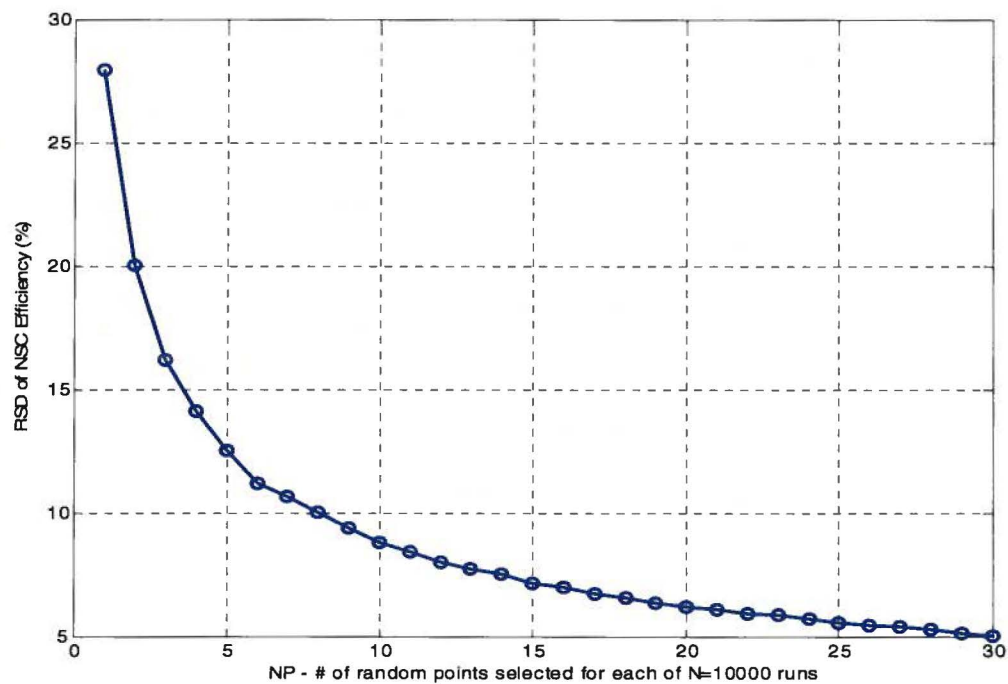


Fig. 9. Zoom view of Fig. 8

Another approach to source location uncertainty determination is to analyze the variation in efficiency for the verification measurements with the WRM sources placed at various locations within the mock volute. The calculated efficiency values for the mock volute and WRM source measurements are tabulated in Table 28. The required source data for the efficiency calculations are provided in Table 29. Fig. 10 displays these data as a function of the source position (center, 1/4 radius, 1/2 radius, and 3/4 radius). The dashed lines are drawn through the average values for each source at the specified position. The RSD of these data is 27.5%. This result is in good agreement with the value determined based on the MCNP point source data.

Table 28. NSC Calculated Efficiencies Based on Mock Volute and WRM Source Measurements

Date	Source	Position	r_i (c/s) ¹	ϵ ³
9/23/13	WRM3	Center	0.56111	0.004192
9/23/13	WRM3	Center	0.69167	0.005168
9/23/13	WRM3	Center	0.64167	0.004794
9/27/13	WRM3	1/4 Radius	0.54444	0.004068
9/27/13	WRM3	1/4 Radius	0.52500	0.003922
9/27/13	WRM3	1/4 Radius	0.54167	0.004047
9/24/13	WRM3	1/2 Radius	0.35278	0.002636
9/24/13	WRM3	1/2 Radius	0.38056	0.002843
9/24/13	WRM3	1/2 Radius	0.45556	0.003404
9/25/13 ²	WRM3	1/2 Radius	0.37778	0.002822
9/25/13 ²	WRM3	1/2 Radius	0.37222	0.002781
9/26/13	WRM3	3/4 Radius	0.27222	0.002034
9/26/13	WRM3	3/4 Radius	0.35000	0.002615
9/26/13	WRM3	3/4 Radius	0.31667	0.002366
9/17/13	WRM7	Center	1.34722	0.004156
9/17/13	WRM7	Center	1.44722	0.004465
9/17/13	WRM7	Center	1.42500	0.004396
9/16/13 ²	WRM7	1/4 Radius	1.26944	0.003916
9/16/13 ²	WRM7	1/4 Radius	1.20833	0.003728
9/20/13	WRM7	1/4 Radius	1.28056	0.003951
9/20/13	WRM7	1/4 Radius	1.17500	0.003625
9/20/13	WRM7	1/4 Radius	1.26944	0.003916
9/18/13	WRM7	1/2 Radius	0.91944	0.002837
9/18/13	WRM7	1/2 Radius	0.81111	0.002502
9/18/13	WRM7	1/2 Radius	1.01944	0.003145
9/19/13	WRM7	3/4 Radius	0.69167	0.002134
9/19/13	WRM7	3/4 Radius	0.72222	0.002228
9/19/13	WRM7	3/4 Radius	0.71389	0.002202
Average Efficiency ²				0.003402
Standard Deviation of Efficiencies ²				0.000937
RSD of Efficiencies (%) ²				27.5

1. see Table 20.
2. Identified data excluded from average and RSD determination to keep consistent weighting of three points per location and source (excluded data were additional measurements not required by the NSC PTV, UCOR-4443).

$$3. \quad \epsilon = \frac{WF_{235}}{m_{cal,U235} \cdot (WF_{234} \cdot R_{n-234} + WF_{235} \cdot R_{n-235} + WF_{238} \cdot R_{n-238})} \cdot r_i$$

Table 29. WRM Source Data used for Efficiency Calculation in Table 28

	WRM3 ³	WRM7 ⁴
WF_{234} (g U-234 / g U)	0.0031	0.00262
WF_{235} (g U-235 / g U)	0.4552	0.379
WF_{238} (g U-238 / g U)	0.5417	0.62362
R_{n-234} (n/s/g U-234) ¹	180	180
R_{n-235} (n/s/g U-235) ²	0.036	0.036
R_{n-238} (n/s/g U-238) ²	0.0175	0.0175
$m_{cal,U\ 235}$ (g U-235)	105.6	247.6

1. BJC/OR-2862
2. LANL 1991
3. Appendix A
4. MCLinc 2008

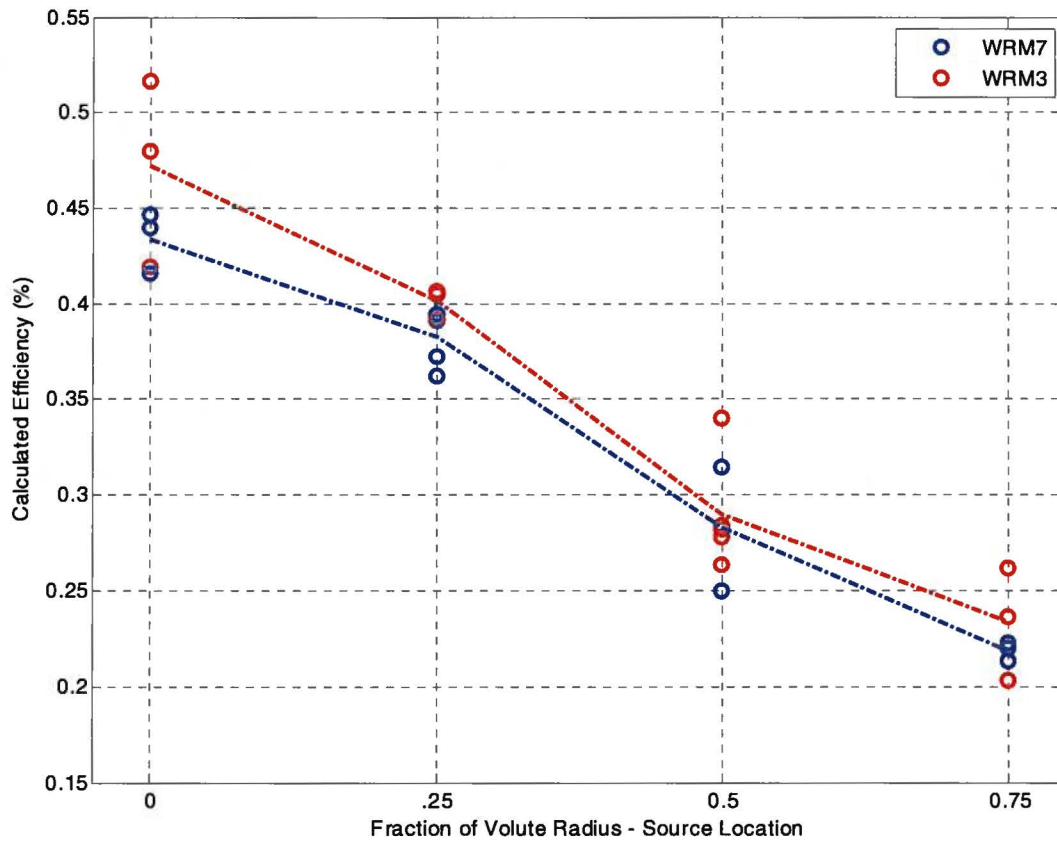


Fig. 10 NSC Calculated Efficiencies Based on Mock Volute and WRM Source Measurements

Based on the two different approaches described above for evaluating the source location uncertainty of the NSC, the value to be applied for the source location RSD of NSC volute measurements is: $\%RSD_{SL,V}=28\%$. This value relies on a minimum amount of assumptions and is consistent with the observed variability from the verification measurements with the mock volute.

5.5 BACKGROUND VARIABILITY

Over the period from 9/11/2013 to 10/25/2013 background measurements were performed with the NSC. A total of 150 one hour background measurements were performed with the mock volute staged in the NSC, and 84 one hour background measurements were performed with the empty NSC. For the purposes of background data collection and analysis, background measurements were performed continuously from the end of the day's operations to the next morning. While these data were not recorded on the field sheets, they were logged electronically in the E-600s. The full set of background data collected is presented in Appendix C. The analysis of background measurements at the NSC is required to establish the observed variability in the background which is due to environmental effects rather than due to detector counting statistics as described in the NSC PTV section 5.5 (UCOR-4443).

The full set of background data were divided into four subsets: background with volute, background with volute logged between 6AM and 8PM, background with empty NSC, background with empty NSC logged between 6AM and 8PM. The NSC operation is expected to be performed within the 6AM to 8PM time period; thus, it is the variability due to environmental effects over that time period which is most applicable. The cumulative set of background data can be reduced to the required unexplained variance by following the methodology described in the NSC PTV section 5.5 (UCOR-4443). The final background variability term and the intermediate terms are presented in Table 30.

Table 30. Background Variability Terms Based on Observed Background Rate During Calibration

Background Data Set	G^1	$\bar{B}_R^{(2)}$	$\sigma_{BR}^2{}^3$	$\sigma_{BCSR}^2{}^4$	$\sigma_{BVR}^2{}^5$	σ_{BVR}
Volute Background, all data	150	1.53	0.00155	4.25E-04	0.00112	0.0335
Volute Background, data logged between 6AM and 8PM	65	1.53	0.00153	4.25E-04	0.00111	0.0333
Empty NSC Background, all data	84	1.42	0.00142	3.95E-04	0.00102	0.0319
Empty NSC Background, data logged between 6AM and 8PM	42	1.42	0.00146	3.95E-04	0.00106	0.0326

1. number of data points in specified data set.
2. average background rate for specified data set
3. variance of background rate, NSC PTV (UCOR-4443), equation 5-22
4. variance due to counting statistics of the background measurements, NSC PTV (UCOR-4443), equation 5-23
5. unexplained variance in observed background, NSC PTV (UCOR-4443), equation 5-24

The background variability determination as reported in Table 30 covers 11 days of operation (limiting the discussion to only those measurements of mock volute backgrounds 9/16-9/27, and excluding 10/25). It is common practice to perform background measurements on the same day as the measurement for a given item, and in many cases the background measurement is immediately before or after the item measurement. If one repeats the background variability calculations on a daily basis, it is expected that the typical observed variability will be lower than that reported in Table 30. Fig. 11 presents the results of these calculations. Of the eleven data points presented, in one case

the σ_{BVR} is ~ 0.036 , in all other cases it is less than the overall result $\sigma_{BVR} = 0.0333$. In two of the eleven cases, the counting statistics contribution is greater than the observed background variability, resulting in $\sigma_{BVR} = 0$.

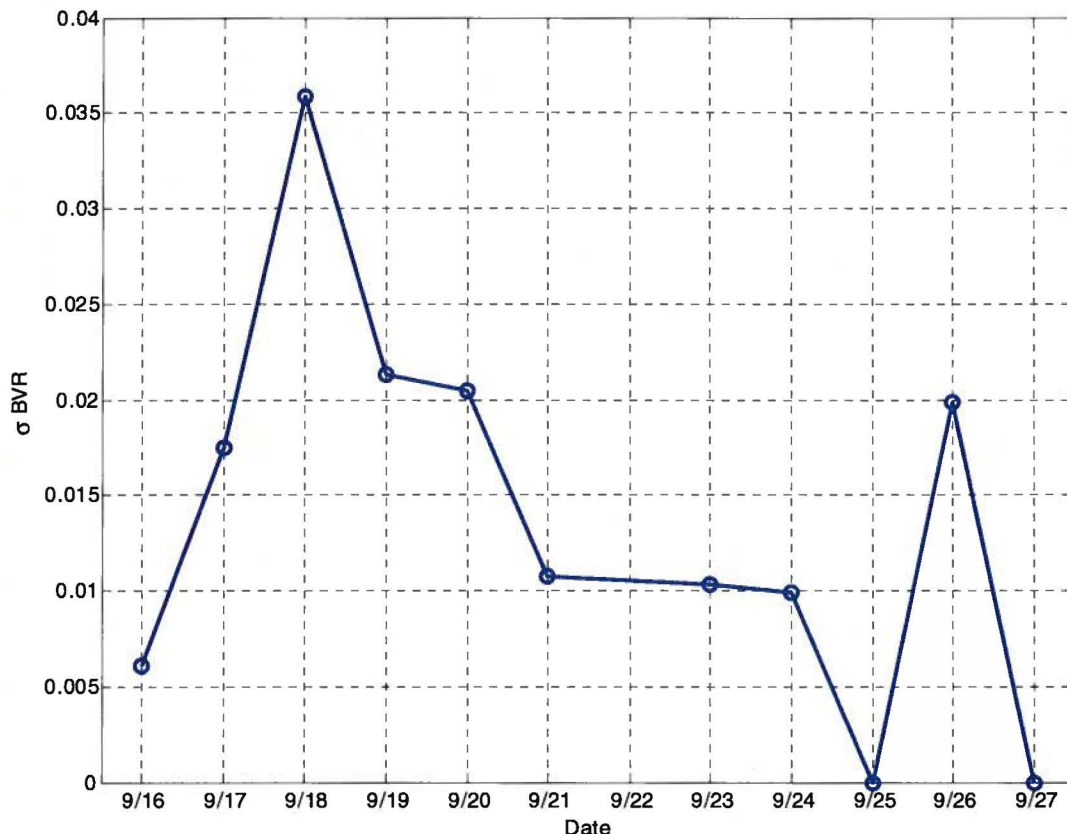


Fig. 11. σ_{BVR} for NSC1 volute background measurements computed on a daily basis

All of the measurements performed and reported in the NSC PTVR (NDA-13-0622) had a paired background measurement. For the purposes of this discussion, a paired background is defined as a background measurement taken prior to the item measurement. The evaluation of background variability considered all of the data collected over multiple days of measurement. With a paired background measurement however, the background variability will not be as large as that computed over multiple days of measurement. Consider the 65 background measurements taken between 6AM and 8PM with the mock volute in NSC1. In 47 of the 65 cases, 2 background measurements were performed within a 4 hour period. This means that over a four hour period, 2 1 hour background measurements were completed with a maximum of 2 hours between the end of one background measurement count and the start of the next. These 47 cases can be evaluated to determine what the reduced background variability term would be considering paired backgrounds. Fig. 12 presents the difference in the count rate for these 47 cases of consecutive background measurements (the full data set is provided in Appendix D). A measure of overall background variability for the case of consecutive backgrounds can be estimated as the standard deviation of these differences, $\sigma = 0.0319$. Note that this overall variability contains the contribution to counting statistics. The counting statistics portion of the uncertainty can be obtained from:

$$\sigma_{\Delta b} = \sqrt{\frac{B_{1,t}}{t_b^2} + \frac{B_{2,t}}{t_b^2} + \frac{B_{1,t-1}}{t_b^2} + \frac{B_{2,t-1}}{t_b^2}}$$

Where all of the count times are the same, $t_b = 3600$ and the B terms are the counts from the upper and lower detectors for the consecutive times $t-1$ and t . Adding the error term to this data results in Fig. 13. Under the assumption that the consecutive background measurements are of identical neutron environments, the difference (b_1-b_2) should be zero. Furthermore, if the only contributing error is due to counting statistics, adding the 95% uncertainty margins due to counting statistics should result in the upper and lower 2σ range containing zero 95% of the time. Reviewing the data in Fig. 13 it is observed that in 3 of the 47 cases, the uncertainty range plotted does not contain zero, i.e. 93.6% of the time the observed difference is explained by counting statistics alone. That being the case the utilization of an additional background variability term could be argued against for the case of paired measurements, since a paired measurement would include a background measurement performed within the 4 hour time period over which the consecutive backgrounds were defined for this analysis.

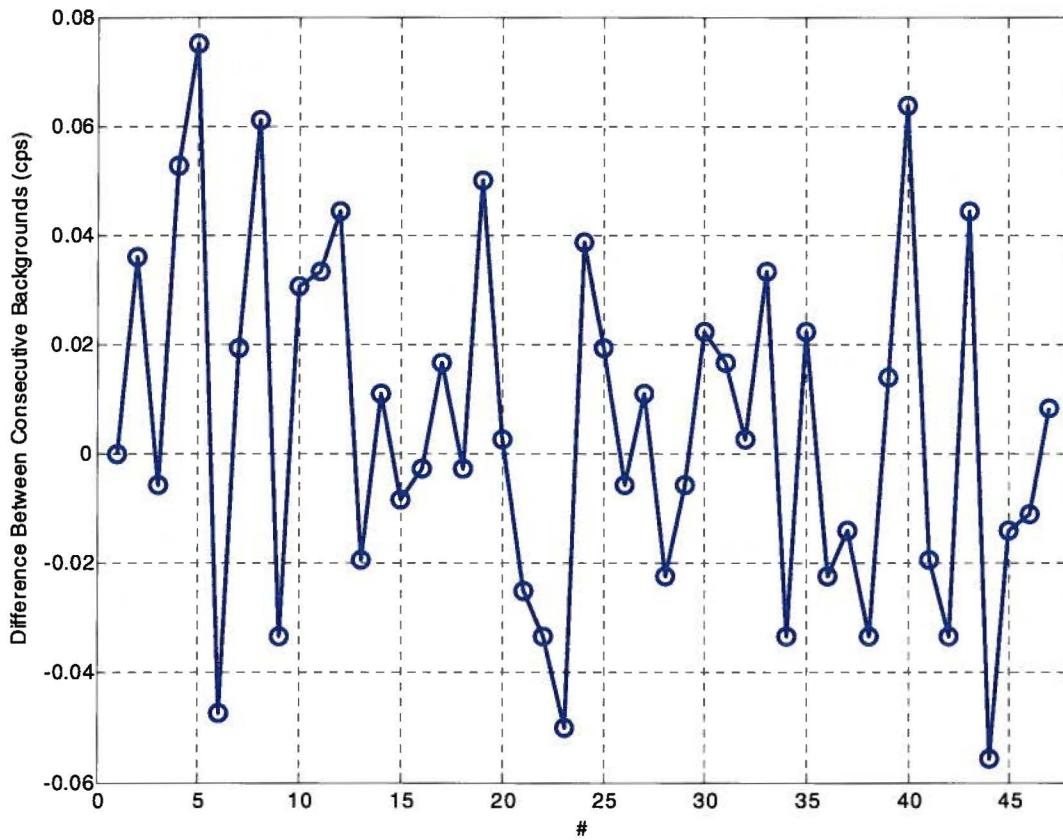


Fig. 12. Difference in count rate between consecutive background measurements with the NSC

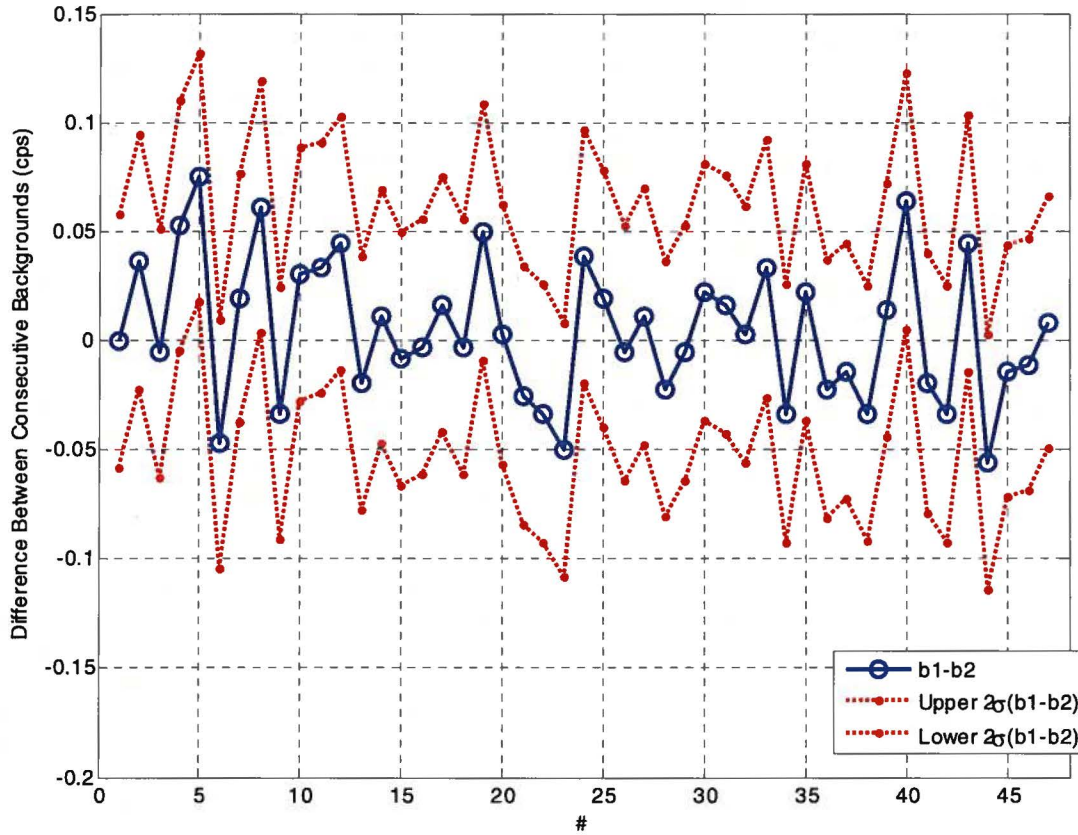


Fig. 13. Difference in count rate between consecutive background measurements with the NSC and the associated 2σ uncertainty margin due to counting statistics

Based on the methodology prescribed in the NSC PTPV (UCOR-4443), the background variability term is determined to be: $\sigma_{BVR} = .0333$. This margin for background variability is based on the overall variability in the background measurements recorded with NSC over the entire calibration period. While the calibration and verification process specified in the NSC PTPV (UCOR-4443) specified paired measurements, the frequency of required background measurements during operations of the NSC in the field is not specified. The analysis of background data presented in this section suggests that under the defined background variability term of $\sigma_{BVR} = .0333$, daily background measurements would be sufficient during normal operations.

5.6 MINIMUM DETECTABLE ACTIVITY

The minimum detectable activities for the empty NSC (S) and for a compressor volute (V), as defined in the NSC PTPV (UCOR-4443), are provided in equations 5-3 and 5-4.

$$MDA_S(gU235) = \frac{WF_{235}}{\bar{E}_{S, Measured, VW} \cdot (WF_{234} \cdot R_{n-234} + WF_{235} \cdot R_{n-235} + WF_{238} \cdot R_{n-238})} \cdot \left[\frac{k^2}{t_F} + 2k\sigma_{B,S} \sqrt{1 + \frac{t_B}{t_F}} \right] \quad (5-3)$$

$$MDA_V(gU235) = \frac{WF_{235}}{\bar{\epsilon}_{V,NSC} \cdot (WF_{234} \cdot R_{n-234} + WF_{235} \cdot R_{n-235} + WF_{238} \cdot R_{n-238})} \cdot \left[\frac{k^2}{t_V} + 2k\sigma_{B,V} \sqrt{1 + \frac{t_C}{t_V}} \right] \quad (5-4)$$

Consistent with the discussion in section 4 regarding the assumptions of the form and hydration state of the uranium compound and the neutron emission rates due to the presence of the uranium isotopes. The assumed material form is fully hydrated UO_2F_2 , and all measured neutrons are assumed to be due to the alpha decay of U-234 inducing (α, n) reactions with fluorine at a rate of $R_{n-234} = 180$ n/s/g U-234; accordingly, $R_{n-235} = R_{n-238} = 0$. Furthermore, the foreground and background count times can be set equal to one another since all count times are the same, i.e., $t_F = t_B = t_V = t_C = t$. For a 95% confidence level for one-tailed statistics, the probability of false positives (Type I error, α) and missed detections (Type II error, β) are 5%. Assuming that the random errors are normally distributed, the constant k is assigned the value of 1.645. With these considerations, the MDA equations can be reduced to the forms shown in equations 5-5 and 5-6.

$$MDA_S(gU235) = \frac{WF_{235}/WF_{234}}{\bar{\epsilon}_{S,Measured,VW} \cdot R_{n-234}} \cdot \left[\frac{2.71}{t} + 4.65\sigma_{B,S} \right] \quad (5-5)$$

$$MDA_V(gU235) = \frac{WF_{235}/WF_{234}}{\bar{\epsilon}_{V,NSC} \cdot R_{n-234}} \cdot \left[\frac{2.71}{t} + 4.65\sigma_{B,V} \right] \quad (5-6)$$

Table 31 provides the intermediate terms and final MDA results for the set of verification measurements performed with NSC1, including those with a source in the empty NSC space, and those with the mock volute. The MDA for compressor volute measurements with the NSC is ~29 g U-235.

Table 31. Minimum Detectable Activity Calculations for NSC Verification Measurements

Source	Position	Date	WF_{235} / WF_{234}^1 (g U-235/g U-234)	C (counts)	t_C (seconds)	σ_{BVR}^2 ²	$\sigma_{B,V}^2$ ³	$\epsilon_{V,NSC}$ ⁵	R_{n-234}^7 n/s/g U-234	k	$\sigma_{B,V}$ (counts/second)	MDA_V ⁸ (g U-235)
WRM3	Center	9/23/13	149	5570	3600	0.00111	0.001539	0.005159	180	1.645	0.039226	29.4
WRM3	Center	9/23/13	149	5390	3600	0.00111	0.001525	0.005159	180	1.645	0.039048	29.3
WRM3	Center	9/23/13	149	5530	3600	0.00111	0.001536	0.005159	180	1.645	0.039187	29.4
WRM3	1/4 Radius	9/27/13	149	5460	3600	0.00111	0.00153	0.005159	180	1.645	0.039118	29.3
WRM3	1/4 Radius	9/27/13	149	5410	3600	0.00111	0.001526	0.005159	180	1.645	0.039068	29.3
WRM3	1/4 Radius	9/27/13	149	5370	3600	0.00111	0.001523	0.005159	180	1.645	0.039029	29.2
WRM3	1/2 Radius	9/24/13	149	5560	3600	0.00111	0.001538	0.005159	180	1.645	0.039216	29.4
WRM3	1/2 Radius	9/24/13	149	5480	3600	0.00111	0.001532	0.005159	180	1.645	0.039137	29.3
WRM3	1/2 Radius	9/24/13	149	5600	3600	0.00111	0.001541	0.005159	180	1.645	0.039255	29.4
WRM3	1/2 Radius	9/25/13	149	5610	3600	0.00111	0.001542	0.005159	180	1.645	0.039265	29.4
WRM3	1/2 Radius	9/25/13	149	5620	3600	0.00111	0.001543	0.005159	180	1.645	0.039275	29.4
WRM3	3/4 Radius	9/26/13	149	5560	3600	0.00111	0.001538	0.005159	180	1.645	0.039216	29.4
WRM3	3/4 Radius	9/26/13	149	5440	3600	0.00111	0.001529	0.005159	180	1.645	0.039098	29.3
WRM3	3/4 Radius	9/26/13	149	5490	3600	0.00111	0.001533	0.005159	180	1.645	0.039147	29.3
WRM7	Center	9/17/13	145	5310	3600	0.00111	0.001519	0.005159	180	1.645	0.038969	28.4
WRM7	Center	9/17/13	145	5290	3600	0.00111	0.001517	0.005159	180	1.645	0.03895	28.4
WRM7	Center	9/17/13	145	5480	3600	0.00111	0.001532	0.005159	180	1.645	0.039137	28.5
WRM7	1/4 Radius	9/20/13	145	5500	3600	0.00111	0.001533	0.005159	180	1.645	0.039157	28.6
WRM7	1/4 Radius	9/20/13	145	5490	3600	0.00111	0.001533	0.005159	180	1.645	0.039147	28.5
WRM7	1/4 Radius	9/20/13	145	5550	3600	0.00111	0.001537	0.005159	180	1.645	0.039206	28.6
WRM7	1/4 Radius	9/16/13	145	5380	3600	0.00111	0.001524	0.005159	180	1.645	0.039039	28.5
WRM7	1/4 Radius	9/16/13	145	5430	3600	0.00111	0.001528	0.005159	180	1.645	0.039088	28.5
WRM7	1/2 Radius	9/18/13	145	5100	3600	0.00111	0.001502	0.005159	180	1.645	0.038761	28.3
WRM7	1/2 Radius	9/18/13	145	5370	3600	0.00111	0.001523	0.005159	180	1.645	0.039029	28.5
WRM7	1/2 Radius	9/18/13	145	5200	3600	0.00111	0.00151	0.005159	180	1.645	0.03886	28.3
WRM7	3/4 Radius	9/19/13	145	5260	3600	0.00111	0.001515	0.005159	180	1.645	0.03892	28.4
WRM7	3/4 Radius	9/19/13	145	5380	3600	0.00111	0.001524	0.005159	180	1.645	0.039039	28.5
WRM7	3/4 Radius	9/19/13	145	5540	3600	0.00111	0.001536	0.005159	180	1.645	0.039196	28.6

Source	Position	Date	WF_{235} / WF_{234}^1 (g U-235/g U-234)	B (counts)	t_B (seconds)	σ_{BVR}^2 ²	$\sigma_{B,S}^2$ ⁴	$\epsilon_{10,S,Measured}$ ⁶	R_{n-234}^7 n/s/g U-234	k	$\sigma_{B,S}$ (counts/second)	MDA_S ⁹ (g U-235)
WRM3	Empty NSC	9/14/13	149	5270	3600	0.00111	0.001516	0.003507	180	1.645	0.0389	42.9
WRM7	Empty NSC	9/14/13	145	5270	3600	0.00111	0.001516	0.003507	180	1.645	0.0389	41.8

1. WRM3 (Appendix A), WRM7 (MCLinc 2008)
2. Table 30
3. NSC PTPV (UCOR-4443), equation 5-30
4. NSC PTPV (UCOR-4443), equation 5-29
5. Table 15
6. Table 11
7. BJC/OR-2862
8. Equation 5-6
9. Equation 5-5

5.7 TOTAL MEASUREMENT UNCERTAINTY

The individual components of the TMU calculation for the NSC were evaluated in sections 5.1 through 5.5. Table 32 summarizes the results for each of these components along with the calculated TMU according to the NSC PTV (UCOR-4443) equations 5-31 and 5-32. The average percent TMU for the verification measurements with a source in the mock volute was ~30%. The TMU for the bare source in the empty NSC as shown in Table 32 is lower due to the use of a single measured efficiency and corresponding uncertainties; including a source location uncertainty term set to zero. This calculation was completed for evaluation purposes only. The NSC is not designed for quantitative measurements without a compressor volute (or mock volute with a known source).

Table 32. Total Measurement Uncertainty Calculations for NSC Verification Measurements

Source	Position	Date	$m_{U-235,V}^1$ (g U-235)	$\epsilon_{V,NSC}^3$	$\%RSD_{CS,V}^5$	$\sigma_{CS,V}^7$ (g U-235)	$\%RSD_{CCS,V}^9$	$\sigma_{CCS,V}^{11}$ (g U-235)	$\%RSD_{CM}^{13}$	$\sigma_{CM,V}^{14}$ (g U-235)	$\%RSD_{SL,V}^{16}$	$\sigma_{SL,V}^{18}$ (g U-235)	$\sigma_{BV,V}^{20}$ (g U-235)	$\%RSD_{BV,V}^{22}$	TMU_V^{24} (g U-235)	$\%TMU_V^{26}$
WRM3	Center	9/23/13	90.04	0.005159	5.68	5.11	0.638	0.574	5	4.50	28	25.2	5.34	5.93	26.7	29.6
WRM3	Center	9/23/13	110.99	0.005159	4.63	5.13	0.638	0.708	5	5.55	28	31.1	5.34	4.81	32.4	29.2
WRM3	Center	9/23/13	102.96	0.005159	5.01	5.15	0.638	0.656	5	5.15	28	28.8	5.34	5.19	30.2	29.3
WRM3	1/4 Radius	9/27/13	87.36	0.005159	5.79	5.06	0.638	0.557	5	4.37	28	24.5	5.34	6.12	25.9	29.7
WRM3	1/4 Radius	9/27/13	84.24	0.005159	5.97	5.03	0.638	0.537	5	4.21	28	23.6	5.34	6.34	25.1	29.8
WRM3	1/4 Radius	9/27/13	86.92	0.005159	5.78	5.02	0.638	0.554	5	4.35	28	24.3	5.34	6.15	25.8	29.7
WRM3	1/2 Radius	9/24/13	56.61	0.005159	8.76	4.96	0.638	0.361	5	2.83	28	15.9	5.34	9.44	17.7	31.2
WRM3	1/2 Radius	9/24/13	61.06	0.005159	8.11	4.95	0.638	0.389	5	3.05	28	17.1	5.34	8.75	18.8	30.8
WRM3	1/2 Radius	9/24/13	73.10	0.005159	6.91	5.05	0.638	0.466	5	3.65	28	20.5	5.34	7.31	22.1	30.2
WRM3	1/2 Radius	9/25/13	60.62	0.005159	8.25	5.00	0.638	0.386	5	3.03	28	17.0	5.34	8.81	18.7	30.9
WRM3	1/2 Radius	9/25/13	59.73	0.005159	8.37	5.00	0.638	0.381	5	2.99	28	16.7	5.34	8.95	18.5	31.0
WRM3	3/4 Radius	9/26/13	43.68	0.005159	11.2	4.90	0.638	0.278	5	2.18	28	12.2	5.34	12.2	14.4	32.9
WRM3	3/4 Radius	9/26/13	56.16	0.005159	8.74	4.91	0.638	0.358	5	2.81	28	15.7	5.34	9.51	17.5	31.2
WRM3	3/4 Radius	9/26/13	50.81	0.005159	9.66	4.91	0.638	0.324	5	2.54	28	14.2	5.34	10.5	16.2	31.8
WRM7	Center	9/17/13	210.37	0.005159	2.56	5.40	0.638	1.34	5	10.5	28	58.9	5.20	2.47	60.3	28.7
WRM7	Center	9/17/13	225.99	0.005159	2.41	5.45	0.638	1.44	5	11.3	28	63.3	5.20	2.30	64.7	28.6
WRM7	Center	9/17/13	222.52	0.005159	2.47	5.50	0.638	1.42	5	11.1	28	62.3	5.20	2.34	63.8	28.7
WRM7	1/4 Radius	9/20/13	199.96	0.005159	2.71	5.42	0.638	1.27	5	10.0	28	56.0	5.20	2.60	57.4	28.7
WRM7	1/4 Radius	9/20/13	183.48	0.005159	2.92	5.35	0.638	1.17	5	9.17	28	51.4	5.20	2.83	52.7	28.7
WRM7	1/4 Radius	9/20/13	198.23	0.005159	2.74	5.43	0.638	1.26	5	9.91	28	55.5	5.20	2.62	56.9	28.7
WRM7	1/4 Radius	9/16/13	198.23	0.005159	2.71	5.37	0.638	1.26	5	9.91	28	55.5	5.20	2.62	56.9	28.7
WRM7	1/4 Radius	9/16/13	188.69	0.005159	2.84	5.35	0.638	1.20	5	9.43	28	52.8	5.20	2.76	54.2	28.7
WRM7	1/2 Radius	9/18/13	143.58	0.005159	3.51	5.04	0.638	0.915	5	7.18	28	40.2	5.20	3.62	41.5	28.9
WRM7	1/2 Radius	9/18/13	126.66	0.005159	4.00	5.07	0.638	0.807	5	6.33	28	35.5	5.20	4.11	36.8	29.0
WRM7	1/2 Radius	9/18/13	159.19	0.005159	3.23	5.15	0.638	1.01	5	7.96	28	44.6	5.20	3.27	45.9	28.8
WRM7	3/4 Radius	9/19/13	108.01	0.005159	4.58	4.95	0.638	0.689	5	5.40	28	30.2	5.20	4.81	31.6	29.2
WRM7	3/4 Radius	9/19/13	112.78	0.005159	4.45	5.01	0.638	0.719	5	5.64	28	31.6	5.20	4.61	32.9	29.2
WRM7	3/4 Radius	9/19/13	111.48	0.005159	4.55	5.07	0.638	0.711	5	5.57	28	31.2	5.20	4.66	32.5	29.2

Source	Position	Date	$m_{U-235,S}^{25}$ (g U-235)	$\epsilon_{10,S,Measured}^{4}$	$\%RSD_{CS,S}^{6}$	$\sigma_{CS,S}^{8}$ (g U-235)	$\%RSD_{CCS,S-10}^{10}$	$\sigma_{CCS,S-10}^{12}$ (g U-235)	$\%RSD_{CM}^{13}$	$\sigma_{CM,S}^{15}$ (g U-235)	$\%RSD_{SL,S-10}^{17}$	$\sigma_{SL,S-10}^{19}$ (g U-235)	$\sigma_{BV,S-10}^{21}$ (g U-235)	$\%RSD_{BV,V}^{23}$	TMU_S^{25} (g U-235)	$\%TMU_S^{27}$
WRM3	Empty NSC (0,0,0)	9/14/13	110.14	0.003507	6.58	7.25	6.45	7.10	5	5.51	0	0	7.86	7.14	14.0	12.7
WRM7	Empty NSC (0,0,0)	9/14/13	260.94	0.003507	2.96	7.72	6.45	16.8	5	13.0	0	0	7.65	2.93	23.9	9.16

1. Equation 4-2
2. Equation 4-1
3. Table 15
4. Table 11
5. Table 22
6. Table 21
7. NSC PTVP (UCOR-4443), equation 5-6
8. NSC PTVP (UCOR-4443), equation 5-5
9. NSC PTVP (UCOR-4443), equation 5-10
10. $\%RSD_{CCS,S-10}$ is the relative standard deviation from calibration counting statistics from calibration point 10 only (0,0,0).
11. NSC PTVP (UCOR-4443) equation 5-12
12. $\sigma_{CCS,S-10}$ is computed from $\%RSD_{CCS,S-10}$
13. Section 4.3
14. NSC PTVP (UCOR-4443) equation 5-15
15. NSC PTVP (UCOR-4443) equation 5-14
16. Section 4.4
17. $\%RSD_{SL,S-10}$ is set to zero since the source was placed at the origin (calibration point location 10)
18. NSC PTVP (UCOR-4443) equation 5-20a
19. $\sigma_{SL,S-10}$ is computed from $\%RSD_{SL,S-10}$
20. NSC PTVP (UCOR-4443), equation 5-26, where $R_{n-235} = R_{n-238} = 0$
21. NSC PTVP (UCOR-4443), equation 5-25, where $R_{n-235} = R_{n-238} = 0$, and the efficiency is set to $\epsilon_{10,S,Measured}$.
22. $\%RSD_{BV,V} = \sigma_{BV,V} / m_{U-235,V}$
23. $\%RSD_{BV,S} = \sigma_{BV,S} / m_{U-235,S}$
24. NSC PTVP (UCOR-4443), equation 5-32
25. NSC PTVP (UCOR-4443), equation 5-31
26. $\%TMU_V = TMU_V / m_{U-235,V}$
27. $\%TMU_S = TMU_S / m_{U-235,S}$

6. Calibration Confirmation Results

As stated in the NSC PTV (UCOR-4443), a calibration confirmation measurement is required using a compressor which was measured in the UNCS to contain >100 g U-235 (nominal value). On 11/16/2012, compressor J03613 was measured in the UNCS and was quantified to contain 287.03 g U-235 with a TMU of 16.85 g U-235 (NDA-12-0646). The associated volute was removed from the compressor and staged on a pallet during the mining process. The J03613 compressor volute and pallet assembly was measured in the UNCS on 7/24/2013: 90.12 g U-235, with a TMU of 15.72 (NDA-13-0402). This result represents the reference value for the calibration confirmation measurement. The same volute/pallet assembly was measured at the NSC on 10/25/2013 (NDA-13-0622). The reported neutron count data from the NSC are provided in Table 33 along with all of the intermediate and final parameters required for the MDA and TMU calculations.

Table 33. NSC Calibration Confirmation Data

Item	Compressor Volute - J03613
Date	10/25/2013
V_1 (counts)	3990
V_2 (counts)	3750
V (counts)	7740
t_V (seconds)	3600
C_1 (counts)	2630
C_2 (counts)	2800
C (counts)	5430
t_C (seconds)	3600
r (c/s)	0.642
$\mathcal{E}_{V,NSC}$	0.005159
WF_{235} / WF_{234} (g U-235/g U-234)	154
R_{n-234} (n/s/g U-234)	180
$m_{U-235,V}$ (g U-235)	106
σ_r	0.0319
$\%RSD_{CS,V}$	4.97
$\sigma_{CS,V}$ (g U-235)	5.29
$\%RSD_{CCS,V}$	0.638
$\sigma_{CCS,V}$ (g U-235)	0.678
$\%RSD_{CM}$	5
$\sigma_{CM,V}$ (g U-235)	5.32
$\%RSD_{SL,V}$	28
$\sigma_{SL,V}$ (g U-235)	29.8
σ_{BVR}	0.0333

$\sigma_{BV,V}$ (g U-235)	5.52
TMU_V (g U-235)	31.2
k	1.645
$\sigma_{B,V}$	0.0391
MDA_V	30.3

The UNCS measurement of the J03613 volute was 90.12 g U-235, with a TMU of 15.72 (NDA-13-0402). The NSC measurement of the J03613 volute was 106 g U-235, with a TMU of 31.2 g U-235. The two quantitative results agree within instrument uncertainty; therefore, the calibration confirmation requirement of the NSC PTVP (UCOR-4443) has been met.

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7. Performance Test and Evaluation Summary

The NSC was designed for quantitative Nondestructive Assay (NDA) measurements of compressor volutes from the K25/K27 Buildings.

The required measurements of the NSC PTVP (UCOR-4443) were completed according to the *Calibration of NDA Equipment* Procedure (PROC-DE-0714) and the *Quantitative Measurements Using the Neutron Slab Counter* Procedure (PROC-DE-0723). The measurement data were compiled and reported in the NSC PTVR (NDA-13-0622). This document, the PTVE, reviewed and analyzed the data collected to evaluate the performance of the NSC for its intended purpose. Based on this analysis and its supporting documentation, a commissioning report for the NSC defining its proper use and limitations will be prepared.

The required measurements and calculations for the NSC instrument and method qualification were completed as described in the NSC PTVP (UCOR-4443). Section 2 of this document describes the initial control measurements performed to establish a measurement control baseline. The calibration test results are presented in section 3, including descriptions and discussions on the data collected and a determination of the NSC efficiency. The NSC system efficiency for compressor volute measurements, based on the calibration measurements as reported in the NSC PTVR (NDA-13-0622), is $\epsilon_{V,NSC} = 0.5159\%$. Future NSC system calibrations will produce slight differences in efficiency values due to the dependence on the calibration measurements.

The data collected for the calibration verification and performance tests as reported in the NSC PTVR (NDA-13-0622) are provided in section 4. The quantitative determinations of U-235 mass are provided for each verification measurement along with the required bias and average bias calculations. The total average bias for the verification measurements with a source placed at the center and $\frac{1}{4}$ radius of the mock volute is -13.9%. For further discussion, refer to section 4.

Section 5 evaluates the uncertainty terms which contribute to the NSC TMU and MDA. The most significant contribution to the TMU is due to the source location uncertainty (28%), driven by the variation in efficiency across the horizontal plane at the center of the NSC calibration space volume. Combining the source location uncertainty term with the other uncertainty terms in the TMU calculation results in an average TMU of ~30%. After quantifying the uncertainty terms related to background variability, the MDA for the NSC verification measurements was determined to be ~29 g U-235. This result meets the DQO set in the NSC PTVP (UCOR-4443) of 50% of the shipping limit (252 g U-235).

The calibration confirmation measurements are described in section 6. The compressor volute confirmation measurement resulted in a nominal quantitative value of 106 g U-235, with a TMU of 31.2 g U-235. This result is in good agreement with the UNCS measurement for the same item 90.12 g U-235, with a TMU of 15.72. The two quantitative results agree within instrument uncertainty; therefore, the calibration confirmation requirement of the NSC PTVP (UCOR-4443) has been met.

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8. References

BJC/OR-2862, Rev 0, August 2007: Recommendations of $^{235}\text{U}/^{234}\text{U}$ Ratios and Alpha-Neutron Yields for the K-25/K-27 D&D Neutron NDA Methodology.

Kellex DWG MIE702500A718

LANL 1991, Passive Nondestructive Assay of Nuclear Materials, NUREG-CR-5550, LA-UR-90-732, Los Alamos National Laboratory, March 1991.

MCLinc 2008, Preparation and Testing Report for Technical Support to NDA Source Specification, Prepared by Materials and Chemistry Laboratory, MCLinc Project # BJC001990, Final Report, 5/14/2008.

NDA-12-0646, UNCS: 11/16/2012, UCOR NDA.

NDA-13-0402, UNCS: 7/24/2013, UCOR NDA.

NDA-13-0622, K-1066 F Pad: 10/25/2013: Neutron Slab Counter: Performance Test and Validation Report, UCOR NDA.

PROC-DE-0714, Calibration of NDA Equipment

PROC-DE-0723, Quantitative Measurements Using the Neutron Slab Counter

UCOR-4443, *Neutron Slab Counter Performance Test and Validation Plan*.

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APPENDIX A.
SOURCE CERTIFICATES

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Certificate for Working Reference Material (WRM) Sealed Radioactive Source

Produced by: Materials and Chemistry Laboratory, Inc
ETTP Building K-1006 2010 Highway 58 Suite 1000
Oak Ridge, TN 37830-1702 (P) 865-576-4138 (F) 865- 576-8558

Working Reference Material Sealed Radioactive Source

Model Number: 304L-HDF4-300
Serial Number: **WRM-3**
Radionuclide: U^{235} (45.52 % assay) ~ 105.6-g
Radionuclide Impurities: Other isotopes of Uranium (U^{234} ~ 0.71-g)
Description: NDA Working Reference Material Sealed Source
Stable Hydrate of Solid Uranyl Fluoride, Lot ID 3C99DMK3KT

Active Length: ~4.62-inch (In vertical position)
Active diameter: 1.81-inch (In vertical position)
Overall Length: 9.0-inch
Overall Diameter: 2.0-inch

ANSI Classification: ANSI 07C22212

Activity: $U(\text{total}) = 231.9\text{-g}$ (~ 4.68E-03 Ci)

Radiation Output:
Quantity Measured: Beta/Gamma
Result: ~ 1.5 mR/hr at contact

Test for Freedom from surface Contamination:
Method: Dry Wipe Test
Result: Passed (< 5 dpm alpha)

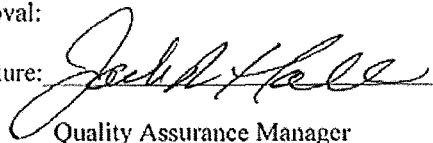
Test for Freedom from Leakage:
Method: Helium Test
Result: Passed (< 1×10^{-5} atm cc/s)
(Leak rate = 1.2×10^{-9} atm cc/s)

Date of manufacture: March 20, 2008

This Certificate and the information contained herein complies with the requirements of
ANSI N43.6-2007

Approval:

Signature:

 Date: 5/16/08

Quality Assurance Manager

FTC-CF-835

INFORMATION SHEET

²⁵²Cf NEUTRON SOURCE
SPECIAL FORM TESTING CERTIFICATION NO. 60

Source Identification Number: SR-Cf-1315

Shipped To: Frontier Technology Corp., 1641 Burnett Drive, Xenia, OH 45385

Shipping Capsule Dwg. No.: M-12541-CP-099 E-1, Items 1a, 1b, 1c, and 1d

Closure Date: 6/20/96

Decontamination and Closure Tests

Method: After closure, capsule surfaces were decontaminated until all exterior surfaces were free of contamination (≤ 9 d/m alpha and < 100 d/m beta-gamma) as determined by a wipe test. The assembly was immersed in a helium atmosphere at a pressure of 300 pounds per square inch for a period of 30 minutes, then transferred to a helium leak detector. The leak detector has a minimum sensitivity of 1.0×10^{-8} standard cubic centimeters of helium per second.

Tests: The finished capsule was found free of detectable leakage and free of transferrable contamination on 6/20/96.

Californium Content:

Isotopic Composition: The californium stock materials used to prepare the Pd-Cf₂O₃ composite material in the special form shipping capsule SR-Cf-1315 are identified by Batch Codes CXCF-537 and CX-AF063. The calculated isotopic mass distribution of this composite lot of material, identified as COMP69, is listed in Table 1. The ²⁴⁸Cm decay product was last separated from this material as of 11/17/95.

Form: The californium is in the form of Pd-Cf₂O₃ composite which has been heated to 1600°C for 60 minutes to melt the palladium and homogenize the mixture. The resulting pellets were rolled to nearly square wires with widths across flats of ≤ 0.049 in.

Source Strength: The neutron emission rate of the finished assembly SR-Cf-1315 was determined by comparing its strength to that of NSD-119, a reference ²⁵²Cf source traceable to the national reference radium-beryllium source, NS-1, at the National Institute of Standards and Technology. The comparison was made by inserting the capsule assembly into a moderator containing an array of fission counters and measuring the subsequent induced electric current by a picoammeter. The total neutron emission rate of this assembly was found to be 8.6420×10^9 neutrons per second with a relative standard error of ± 0.30 % as of 6/24/96.

²⁵²Cf Content: The ²⁵²Cf content of this assembly has been inferred from the measured neutron emission rate by correcting the gross emission rate by a factor of 0.99899, the fraction of the spontaneous fission neutrons

emanating from the isotope ^{252}Cf , and by dividing by 2.31434×10^6 neutrons per second per microgram. These values may be calculated from the isotopic compositions listed in Table 1, the relative quantities listed in the accompanying letter, and from the nuclear data listed in Table 2. The equivalent ^{252}Cf content on the assay date, 6/24/96, was computed to be 3.730.3 μg with a relative standard error of $\pm 0.30\%$. Due to propagation of errors along the chain of traceability and also to non-random errors, including variations in source geometry, the overall accuracy of the assay is estimated to be $\pm 3\%$ limit of error.

The radiation intensity one meter from a ^{252}Cf source in air at standard atmospheric conditions and without contributions from scattering media is nominally 2210 mrem/h fast neutrons plus 190 mR/h gamma for each milligram of ^{252}Cf in the capsule.

Table 1. Isotopic Mass Analyses

Cf Batch Code Mass Analysis Date	COMP69 6/30/96
Nuclide	Isotopic Composition (atom %)
^{249}Cf	6.627
^{250}Cf	12.661
^{251}Cf	4.060
^{252}Cf	76.651
^{254}Cf	0.00003

Table 2. Assumed Nuclear Parameters

Nuclide	Half-Life	Alpha branching ratio	Spont. fission branching ratio	ν
^{249}Cf	351 y	~ 1.0	5.2×10^{-9}	3.4
^{250}Cf	13.20 y	0.99921	0.00079	3.53
^{251}Cf	898 y	~ 1.0	9.0×10^{-6}	3.7
^{252}Cf	2.645 y	0.96904	0.03096	3.768
^{253}Cf	17.81 d	0.0031		
^{254}Cf	61.9 d	0.00299	0.99701	3.93

Attested J. B. Krauer Date 6/25/96

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APPENDIX B.
MATLAB CODE TO EVALUATE NSC MCNP SOURCE LOCATION
UNCERTAINTY

```

% Generate Source Location Error by selecting NP random points from the
% population of 2450 MCNP source data points. Determine the average
% efficiency over the NP points. Repeat N times (N=10000). Determine the
% standard deviation of the N runs for a given number of points NP. Repeat
% this process for additional numbers of points NP.

```

```

load NSC_Error.txt; % load MCNP data file
n=length(NSC_Error);

```

```

% SET PARAMETERS
a=1; %min, max integer
b=n;
N=10000; % Number of random integers to obtain

```

```

for NP=1:750; % # of points to average over

```

```

% Determine random number generator parameters for reproducibility
defaultStream = RandStream.getDefaultStream
if defaultStream.Seed == datenum(date)
else
    s = RandStream.create('mt19937ar','seed',datenum(date));
    fprintf(['Random Number Generator Seed Set to ' num2str(datenum(date))
'\n' ]);
    RandStream.setDefaultStream(s);
end
savedState = defaultStream.State;
s=RandStream.getDefaultStream;

```

```

% Generate NP random integers without replacement over the interval [a:b]
% and repeat N times. For each new run all data points are replaced.

```

```

num_rand=0;
RN=zeros(N,NP);
k=0;
    while k<N;
        SQ=[];
        while length(SQ)<NP;
            sq = randi([a b],1,1);
            if sum(find(SQ==sq))==0;
                SQ=[SQ sq];
            end
        end
        k=k+1;
        RN(k,:)=SQ;
        % save the kth iteration k=1:N for the number of points NP
        E(k,NP)=mean(NSC_Error(SQ',7));
    end;
% Save average efficiency file
    save E E;
% define filename
    savefile = ['RN' num2str(NP) '.mat']
% save filename for each number of random points selected (NP)
    save(savefile, 'RN','s','savedState','a','b','N');
end

```

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APPENDIX C.
NSC BACKGROUND DATA

Background Type	Lower Detector (Counts)	Upper Detector (Counts)	Date	Time	Log Time Between 6AM and 8PM?
Empty	2280	2660	09/11/13	10:49	Yes
Empty	2350	2650	09/11/13	13:33	Yes
Empty	2390	2610	09/11/13	16:24	Yes
Empty	2350	2690	09/11/13	18:39	Yes
Empty	2270	2560	09/11/13	19:57	Yes
Empty	2310	2650	09/11/13	20:57	No
Empty	2300	2680	09/11/13	21:57	No
Empty	2290	2670	09/11/13	22:57	No
Empty	2330	2630	09/11/13	23:57	No
Empty	2380	2630	09/12/13	0:58	No
Empty	2350	2700	09/12/13	1:58	No
Empty	2360	2650	09/12/13	2:58	No
Empty	2350	2540	09/12/13	3:58	No
Empty	2410	2650	09/12/13	4:58	No
Empty	2450	2610	09/12/13	5:58	No
Empty	2410	2620	09/12/13	6:58	Yes
Empty	2370	2640	09/12/13	10:49	Yes
Empty	2420	2710	09/12/13	13:14	Yes
Empty	2700	2720	09/12/13	15:30	Yes
Empty	2440	2730	09/12/13	17:32	Yes
Empty	2310	2650	09/12/13	20:05	No
Empty	2370	2690	09/12/13	21:05	No
Empty	2610	2790	09/12/13	22:05	No
Empty	2450	2750	09/12/13	23:05	No
Empty	2430	2690	09/13/13	0:05	No
Empty	2510	2760	09/13/13	1:05	No
Empty	2480	2640	09/13/13	2:05	No
Empty	2560	2850	09/13/13	3:05	No
Empty	2440	2730	09/13/13	4:06	No
Empty	2440	2850	09/13/13	5:06	No
Empty	2430	2860	09/13/13	6:06	Yes
Empty	2340	2760	09/13/13	9:17	Yes
Empty	2470	2710	09/13/13	11:34	Yes
Empty	2400	2850	09/13/13	14:09	Yes
Empty	2580	2880	09/13/13	16:18	Yes
Empty	2480	2840	09/13/13	18:26	Yes
Empty	2460	2840	09/13/13	20:28	No
Empty	2420	2880	09/13/13	21:28	No
Empty	2450	2780	09/13/13	22:28	No
Empty	2460	2880	09/13/13	23:28	No
Empty	2420	2740	09/14/13	0:29	No
Empty	2580	2810	09/14/13	1:29	No
Empty	2450	2750	09/14/13	2:29	No
Empty	2280	2740	09/14/13	3:29	No
Empty	2430	2840	09/14/13	8:09	Yes
Empty	2500	2770	09/14/13	10:44	Yes

Background Type	Lower Detector (Counts)	Upper Detector (Counts)	Date	Time	Log Time Between 6AM and 8PM?
Empty	2410	2720	09/14/13	12:58	Yes
Empty	2460	2630	09/14/13	14:20	Yes
Empty	2500	2790	09/14/13	15:20	Yes
Empty	2470	2830	09/14/13	16:20	Yes
Empty	2430	2700	09/14/13	17:20	Yes
Empty	2380	2780	09/14/13	18:20	Yes
Empty	2480	2730	09/14/13	19:20	Yes
Empty	2390	2690	09/14/13	20:20	No
Empty	2450	2850	09/14/13	21:20	No
Empty	2450	2720	09/14/13	22:20	No
Empty	2390	2780	09/14/13	23:20	No
Empty	2420	2670	09/15/13	0:20	No
Empty	2350	2690	09/15/13	1:20	No
Empty	2310	2620	09/16/13	9:42	Yes
Empty	2360	2610	09/16/13	12:29	Yes
Empty	2440	2580	10/08/13	12:35	Yes
Empty	2370	2720	10/08/13	14:43	Yes
Empty	2450	2760	10/08/13	16:48	Yes
Empty	2440	2830	10/08/13	18:51	Yes
Empty	2390	2660	10/08/13	20:32	No
Empty	2450	2690	10/08/13	21:32	No
Empty	2330	2680	10/09/13	9:08	Yes
Empty	2320	2640	10/09/13	11:16	Yes
Empty	2340	2670	10/09/13	13:25	Yes
Empty	2310	2720	10/09/13	15:41	Yes
Empty	2410	2700	10/09/13	18:19	Yes
Empty	2440	2640	10/09/13	19:44	Yes
Empty	2340	2640	10/09/13	20:44	No
Empty	2420	2780	10/09/13	21:44	No
Empty	2400	2670	10/09/13	22:44	No
Empty	2400	2630	10/09/13	23:44	No
Empty	2380	2710	10/10/13	0:44	No
Empty	2450	2590	10/10/13	1:44	No
Empty	2420	2650	10/10/13	9:28	Yes
Empty	2370	2600	10/10/13	11:42	Yes
Empty	2430	2700	10/10/13	14:11	Yes
Empty	2350	2760	10/10/13	16:27	Yes
Empty	2470	2710	10/10/13	18:32	Yes
Volute	2680	2700	09/16/13	13:48	Yes
Volute	2690	2740	09/16/13	16:24	Yes
Volute	2640	2790	09/16/13	18:49	Yes
Volute	2730	2830	09/16/13	19:49	Yes
Volute	2680	2740	09/16/13	20:49	No
Volute	2690	2740	09/16/13	21:49	No
Volute	2560	2720	09/16/13	22:49	No
Volute	2540	2760	09/16/13	23:49	No

Background Type	Lower Detector (Counts)	Upper Detector (Counts)	Date	Time	Log Time Between 6AM and 8PM?
Volute	2600	2820	09/17/13	0:50	No
Volute	2710	2740	09/17/13	1:50	No
Volute	2620	2670	09/17/13	2:50	No
Volute	2560	2700	09/17/13	3:50	No
Volute	2660	2730	09/17/13	4:50	No
Volute	2670	2650	09/17/13	5:50	No
Volute	2540	2730	09/17/13	6:50	Yes
Volute	2670	2640	09/17/13	13:50	Yes
Volute	2620	2670	09/17/13	16:09	Yes
Volute	2630	2850	09/17/13	18:22	Yes
Volute	2630	2730	09/17/13	20:57	No
Volute	2690	2700	09/17/13	21:57	No
Volute	2710	2790	09/17/13	22:57	No
Volute	2660	2710	09/17/13	23:57	No
Volute	2640	2700	09/18/13	0:57	No
Volute	2740	2610	09/18/13	1:57	No
Volute	2640	2780	09/18/13	2:57	No
Volute	2650	2760	09/18/13	3:57	No
Volute	2710	2620	09/18/13	4:57	No
Volute	2620	2660	09/18/13	5:57	No
Volute	2750	2760	09/18/13	6:57	Yes
Volute	2540	2560	09/18/13	10:04	Yes
Volute	2570	2800	09/18/13	12:12	Yes
Volute	2500	2700	09/18/13	14:19	Yes
Volute	2590	2680	09/18/13	16:24	Yes
Volute	2750	2740	09/18/13	17:42	Yes
Volute	2600	2770	09/18/13	18:42	Yes
Volute	2710	2770	09/18/13	19:42	Yes
Volute	2680	2670	09/18/13	20:42	No
Volute	2770	2840	09/18/13	21:42	No
Volute	2670	2760	09/18/13	22:42	No
Volute	2700	2740	09/18/13	23:42	No
Volute	2720	2710	09/19/13	0:42	No
Volute	2600	2690	09/19/13	1:42	No
Volute	2620	2830	09/19/13	2:42	No
Volute	2610	2750	09/19/13	3:42	No
Volute	2730	2660	09/19/13	4:42	No
Volute	2610	2690	09/19/13	5:43	No
Volute	2610	2700	09/19/13	6:43	Yes
Volute	2570	2690	09/19/13	10:35	Yes
Volute	2640	2740	09/19/13	12:41	Yes
Volute	2730	2810	09/19/13	14:45	Yes
Volute	2720	2750	09/19/13	16:49	Yes
Volute	2670	2840	09/19/13	18:05	Yes
Volute	2680	2800	09/19/13	19:05	Yes
Volute	2700	2700	09/19/13	20:05	No

Background Type	Lower Detector (Counts)	Upper Detector (Counts)	Date	Time	Log Time Between 6AM and 8PM?
Volute	2680	2760	09/19/13	21:05	No
Volute	2660	2820	09/19/13	22:05	No
Volute	2680	2850	09/19/13	23:05	No
Volute	2750	2730	09/20/13	0:05	No
Volute	2750	2800	09/20/13	1:05	No
Volute	2710	2820	09/20/13	2:05	No
Volute	2730	2730	09/20/13	3:05	No
Volute	2680	2760	09/20/13	4:05	No
Volute	2730	2700	09/20/13	5:05	No
Volute	2700	2760	09/20/13	6:05	Yes
Volute	2700	2800	09/20/13	9:18	Yes
Volute	2740	2750	09/20/13	11:20	Yes
Volute	2840	2710	09/20/13	13:29	Yes
Volute	2800	2740	09/20/13	15:34	Yes
Volute	2860	2860	09/20/13	17:40	Yes
Volute	2760	2970	09/20/13	18:40	Yes
Volute	2810	2830	09/20/13	19:40	Yes
Volute	2750	2810	09/20/13	20:40	No
Volute	2760	2910	09/20/13	21:40	No
Volute	2740	2890	09/20/13	22:40	No
Volute	2850	2930	09/20/13	23:40	No
Volute	2740	2860	09/21/13	0:40	No
Volute	2830	2800	09/21/13	1:40	No
Volute	2860	2830	09/21/13	2:40	No
Volute	2880	2910	09/21/13	3:40	No
Volute	2890	3010	09/21/13	4:40	No
Volute	2860	2930	09/21/13	5:40	No
Volute	2830	2920	09/21/13	6:40	Yes
Volute	2740	2890	09/21/13	7:40	Yes
Volute	2720	2850	09/23/13	10:57	Yes
Volute	2610	2780	09/23/13	13:13	Yes
Volute	2710	2820	09/23/13	15:22	Yes
Volute	2760	2840	09/23/13	17:25	Yes
Volute	2760	2820	09/23/13	18:25	Yes
Volute	2740	2880	09/23/13	19:25	Yes
Volute	2740	2900	09/23/13	20:25	No
Volute	2790	2850	09/23/13	21:25	No
Volute	2810	2820	09/23/13	22:25	No
Volute	2620	2760	09/23/13	23:25	No
Volute	2670	2720	09/24/13	0:25	No
Volute	2680	2790	09/24/13	1:25	No
Volute	2760	2820	09/24/13	2:25	No
Volute	2660	2620	09/24/13	3:25	No
Volute	2640	2700	09/24/13	4:25	No
Volute	2650	2770	09/24/13	5:25	No
Volute	2810	2750	09/24/13	10:14	Yes

Background Type	Lower Detector (Counts)	Upper Detector (Counts)	Date	Time	Log Time Between 6AM and 8PM?
Volute	2690	2790	09/24/13	12:19	Yes
Volute	2730	2870	09/24/13	15:23	Yes
Volute	2700	2880	09/24/13	17:27	Yes
Volute	2740	2920	09/24/13	18:27	Yes
Volute	2820	2900	09/24/13	19:27	Yes
Volute	2760	2870	09/24/13	20:27	No
Volute	2830	2810	09/24/13	21:27	No
Volute	2770	2810	09/24/13	22:27	No
Volute	2800	2880	09/24/13	23:27	No
Volute	2800	2840	09/25/13	0:27	No
Volute	2740	2870	09/25/13	1:27	No
Volute	2780	2840	09/25/13	2:27	No
Volute	2760	2830	09/25/13	3:27	No
Volute	2800	2820	09/25/13	4:27	No
Volute	2650	2970	09/25/13	5:27	No
Volute	2750	2860	09/25/13	11:14	Yes
Volute	2770	2850	09/25/13	13:37	Yes
Volute	2880	2860	09/25/13	15:42	Yes
Volute	2810	2810	09/25/13	16:52	Yes
Volute	2820	2880	09/25/13	17:52	Yes
Volute	2770	2850	09/25/13	18:52	Yes
Volute	2760	2810	09/25/13	19:52	Yes
Volute	2770	2930	09/25/13	20:52	No
Volute	2760	2830	09/25/13	21:52	No
Volute	2740	2820	09/25/13	22:52	No
Volute	2830	2850	09/25/13	23:52	No
Volute	2870	2870	09/26/13	0:52	No
Volute	2730	2890	09/26/13	1:52	No
Volute	2770	2870	09/26/13	2:52	No
Volute	2700	2890	09/26/13	3:52	No
Volute	2640	2900	09/26/13	4:52	No
Volute	2780	2820	09/26/13	5:52	No
Volute	2760	2800	09/26/13	9:18	Yes
Volute	2670	2770	09/26/13	11:23	Yes
Volute	2730	2760	09/26/13	13:30	Yes
Volute	2800	2920	09/26/13	15:34	Yes
Volute	2850	2800	09/26/13	16:34	Yes
Volute	2680	2850	09/26/13	17:34	Yes
Volute	2800	2890	09/26/13	18:34	Yes
Volute	2650	2840	09/26/13	19:34	Yes
Volute	2790	2880	09/26/13	20:34	No
Volute	2710	2860	09/26/13	21:34	No
Volute	2690	2790	09/26/13	22:34	No
Volute	2750	2730	09/26/13	23:34	No
Volute	2730	2750	09/27/13	0:34	No
Volute	2660	2800	09/27/13	9:17	Yes

Background Type	Lower Detector (Counts)	Upper Detector (Counts)	Date	Time	Log Time Between 6AM and 8PM?
Volute	2620	2790	09/27/13	11:21	Yes
Volute	2630	2740	09/27/13	13:25	Yes
Volute	2660	2740	09/27/13	15:33	Yes
Volute	2630	2800	10/25/13	11:10	Yes

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APPENDIX D.
NSC CONSECUTIVE BACKGROUND DATA SET

Table D.1. NSC1 Data Set of Consecutive Background Measurements with the Mock Volute

#	Type	B1(t-1) counts	B2(t-1) counts	Date (t-1)	Time (t-1)	B1(t) counts	B2(t) counts	Date (t)	Time (t)	Δ_b (c/s) ¹	$\sigma_{\Delta b}$ (c/s) ²
1	Bkg with Volute	2690	2740	9/16/13	16:24:00	2640	2790	9/16/13	18:49:00	0	0.028948
2	Bkg with Volute	2640	2790	9/16/13	18:49:00	2730	2830	9/16/13	19:49:00	0.036111	0.02912
3	Bkg with Volute	2670	2640	9/17/13	13:50:00	2620	2670	9/17/13	16:09:00	-0.00556	0.028599
4	Bkg with Volute	2620	2670	9/17/13	16:09:00	2630	2850	9/17/13	18:22:00	0.052778	0.028827
5	Bkg with Volute	2540	2560	9/18/13	10:04:00	2570	2800	9/18/13	12:12:00	0.075	0.028423
6	Bkg with Volute	2570	2800	9/18/13	12:12:00	2500	2700	9/18/13	14:19:00	-0.04722	0.028558
7	Bkg with Volute	2500	2700	9/18/13	14:19:00	2590	2680	9/18/13	16:24:00	0.019444	0.028423
8	Bkg with Volute	2590	2680	9/18/13	16:24:00	2750	2740	9/18/13	17:42:00	0.061111	0.028814
9	Bkg with Volute	2750	2740	9/18/13	17:42:00	2600	2770	9/18/13	18:42:00	-0.03333	0.028948
10	Bkg with Volute	2600	2770	9/18/13	18:42:00	2710	2770	9/18/13	19:42:00	0.030556	0.028934
11	Bkg with Volute	2570	2690	9/19/13	10:35:00	2640	2740	9/19/13	12:41:00	0.033333	0.028653
12	Bkg with Volute	2640	2740	9/19/13	12:41:00	2730	2810	9/19/13	14:45:00	0.044444	0.029027
13	Bkg with Volute	2730	2810	9/19/13	14:45:00	2720	2750	9/19/13	16:49:00	-0.01944	0.029147
14	Bkg with Volute	2720	2750	9/19/13	16:49:00	2670	2840	9/19/13	18:05:00	0.011111	0.029107
15	Bkg with Volute	2670	2840	9/19/13	18:05:00	2680	2800	9/19/13	19:05:00	-0.00833	0.02912
16	Bkg with Volute	2700	2800	9/20/13	9:18:00	2740	2750	9/20/13	11:20:00	-0.00278	0.02912
17	Bkg with Volute	2740	2750	9/20/13	11:20:00	2840	2710	9/20/13	13:29:00	0.016667	0.029187
18	Bkg with Volute	2840	2710	9/20/13	13:29:00	2800	2740	9/20/13	15:34:00	-0.00278	0.029253
19	Bkg with Volute	2800	2740	9/20/13	15:34:00	2860	2860	9/20/13	17:40:00	0.05	0.029476
20	Bkg with Volute	2860	2860	9/20/13	17:40:00	2760	2970	9/20/13	18:40:00	0.002778	0.029724
21	Bkg with Volute	2760	2970	9/20/13	18:40:00	2810	2830	9/20/13	19:40:00	-0.025	0.02962
22	Bkg with Volute	2830	2920	9/21/13	6:40:00	2740	2890	9/21/13	7:40:00	-0.03333	0.029633
23	Bkg with Volute	2720	2850	9/23/13	10:57:00	2610	2780	9/23/13	13:13:00	-0.05	0.029081
24	Bkg with Volute	2610	2780	9/23/13	13:13:00	2710	2820	9/23/13	15:22:00	0.038889	0.029027
25	Bkg with Volute	2710	2820	9/23/13	15:22:00	2760	2840	9/23/13	17:25:00	0.019444	0.029305
26	Bkg with Volute	2760	2840	9/23/13	17:25:00	2760	2820	9/23/13	18:25:00	-0.00556	0.029371
27	Bkg with Volute	2760	2820	9/23/13	18:25:00	2740	2880	9/23/13	19:25:00	0.011111	0.029397
28	Bkg with Volute	2810	2750	9/24/13	10:14:00	2690	2790	9/24/13	12:19:00	-0.02222	0.029187
29	Bkg with Volute	2730	2870	9/24/13	15:23:00	2700	2880	9/24/13	17:27:00	-0.00556	0.029371
30	Bkg with Volute	2700	2880	9/24/13	17:27:00	2740	2920	9/24/13	18:27:00	0.022222	0.02945
31	Bkg with Volute	2740	2920	9/24/13	18:27:00	2820	2900	9/24/13	19:27:00	0.016667	0.029633

#	Type	B1(t-1) counts	B2(t-1) counts	Date (t-1)	Time (t-1)	B1(t) counts	B2(t) counts	Date (t)	Time (t)	Δ_b (c/s) ¹	$\sigma_{\Delta b}$ (c/s) ²
32	Bkg with Volute	2750	2860	9/25/13	11:14:00	2770	2850	9/25/13	13:37:00	0.002778	0.029437
33	Bkg with Volute	2770	2850	9/25/13	13:37:00	2880	2860	9/25/13	15:42:00	0.033333	0.029606
34	Bkg with Volute	2880	2860	9/25/13	15:42:00	2810	2810	9/25/13	16:52:00	-0.03333	0.029606
35	Bkg with Volute	2810	2810	9/25/13	16:52:00	2820	2880	9/25/13	17:52:00	0.022222	0.029554
36	Bkg with Volute	2820	2880	9/25/13	17:52:00	2770	2850	9/25/13	18:52:00	-0.02222	0.029554
37	Bkg with Volute	2770	2850	9/25/13	18:52:00	2760	2810	9/25/13	19:52:00	-0.01389	0.029384
38	Bkg with Volute	2760	2800	9/26/13	9:18:00	2670	2770	9/26/13	11:23:00	-0.03333	0.029134
39	Bkg with Volute	2670	2770	9/26/13	11:23:00	2730	2760	9/26/13	13:30:00	0.013889	0.029041
40	Bkg with Volute	2730	2760	9/26/13	13:30:00	2800	2920	9/26/13	15:34:00	0.063889	0.02941
41	Bkg with Volute	2800	2920	9/26/13	15:34:00	2850	2800	9/26/13	16:34:00	-0.01944	0.02962
42	Bkg with Volute	2850	2800	9/26/13	16:34:00	2680	2850	9/26/13	17:34:00	-0.03333	0.029371
43	Bkg with Volute	2680	2850	9/26/13	17:34:00	2800	2890	9/26/13	18:34:00	0.044444	0.029423
44	Bkg with Volute	2800	2890	9/26/13	18:34:00	2650	2840	9/26/13	19:34:00	-0.05556	0.029371
45	Bkg with Volute	2660	2800	9/27/13	9:17:00	2620	2790	9/27/13	11:21:00	-0.01389	0.028961
46	Bkg with Volute	2620	2790	9/27/13	11:21:00	2630	2740	9/27/13	13:25:00	-0.01111	0.028841
47	Bkg with Volute	2630	2740	9/27/13	13:25:00	2660	2740	9/27/13	15:33:00	0.008333	0.028827

* All count times are 3600 seconds

$$1. \Delta_b = \frac{B_{1,t} + B_{2,t}}{3600} - \frac{B_{1,t-1} + B_{2,t-1}}{3600}$$

$$2. \sigma_{\Delta b} = \sqrt{\frac{B_{1,t}}{t_b^2} + \frac{B_{2,t}}{t_b^2} + \frac{B_{1,t-1}}{t_b^2} + \frac{B_{2,t-1}}{t_b^2}}$$

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