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Fission Gas Monitoring System Efficiency Calibration Summary Report

Edward L Reber

May 2020

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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9. Objective / Purpose

The Fission Gas Monitoring System was designed to work in conjunction with the Fuel Accident Condition Simulator Furnace and is used to measure fission gas releases during post-irradiation fuel heating tests. A high-purity helium sweep gas is swept past the heated fuel sample in the furnace and routed to a fission gas monitoring system, which cryogenically traps the krypton (Kr) and xenon (Xe) fission gases. As the radioactive species of the trapped gas decays, high-purity germanium detectors monitor the amount of fission gas in each trap. The primary fission product present in this test is ^{85}Kr, which has a 10.76-year half-life. The presence of ^{85}Kr indicates particle defects and iodine release. There is also the potential for re-irradiating the fuel compacts in the Neutron Radiography Reactor in the Hot Fuel Examination Facility basement. With re-irradiation, it is possible to have xenon fission gas present, specifically ^{133}Xe, which has a 5.243-day half-life. Re-irradiation also produces ^{131}I, which is important for design-basis accidents and regulatory licensing.

This report summarizes the method used to efficiency calibrate the Fission Gas Monitoring System.

10. If revision, please state the reason and list sections and/or page being affected.

N/A

11. Conclusion / Recommendations

The FGMS was calibrated with five certified standards, ranging from 0.924 to 390.8 μCi. This range of activity simulated prospective Advanced Gas Reactor (AGR)-1 fuel failure within the FACS furnace, ranging from an inventory of one failed particle to many failed particles. HPGe detector responses were obtained at three different detector-to-trap differences (i.e., height), with the corresponding collimation shutter width ranging from 0.5 to 11.0 cm. An efficiency calibration curve was generated for each configuration. These measurements enabled the FGMS team to quantify the activity of the fission gas captured within the FGMS CTs.

Efficiency measurements were acquired from December 2009 to November 2011 and performed at the mockup shop (FCF) and HFEF. The FGMS now permanently resides at HFEF. Efficiency measurements were performed during this extended time span because of certified standard availability, budget constraints, facility shutdowns, and other parameters outside the FGMS support team's control.

Measurements provided in this report satisfy the requirements for the AGR-1 fuel post-irradiation examination experiment series. It is recommended that periodic efficiency measurements are performed to ensure that increased usage of the cold traps does not affect their efficiencies.

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APPENDIXES

PROJECT ROLES AND RESPONSIBILITIES

Project Role	Name	Organization	Pages Covered (if applicable)
Performer	Edward Reber	C620	-----
Checker[a]	Ryan Fronk	C620	-----
Independent Reviewer[b]	Michael Reichenberger	B633	-----
CUI Reviewer[c]	-----	-----	-----
Manager[d]	-----	-----	-----
Requestor[ef]	Dawn Scates	C620	-----
Nuclear Safety[f]	N/A	-----	-----
Document Owner[f]	Dawn Scates	C620	-----
Reviewer[f]	Paul Demkowicz	C600	-----
Quality Engineer[f]	Michelle Sharp	H330	

Responsibilities:

a. Confirmation of completeness, mathematical accuracy, correctness of data, and appropriateness of assumptions.

b. Concurrence of method or approach. See definition, LWP-10106.

c. Concurrence with the document's markings in accordance with LWP-11202.

d. Concurrence of procedure compliance. Concurrence with method/approach and conclusion.

e. Authorizes commencement of work of the engineering deliverable. See Appendix A.

f. Concurrence with the document's assumptions and input information. See definition of "acceptance," LWP-10200.

NOTE: *Delete or mark "N/A" for project roles not engaged. Include ALL personnel and their roles listed above in the eCR system. The list of the roles above is not all inclusive. If needed, the list can be extended or reduced.*

SCOPE AND BRIEF DESCRIPTION

Efficiency calibration of the Fission Gas Monitoring System (FGMS) consists of first loading the liquid-nitrogen cooled cold trap (CT) with a ^{133}Xe (81 keV) and/or ^{85}Kr (514 keV) gas source. The source is then counted with the detector at various distances measured from the bottom of the CT, and with various collimator shutter widths. The thirteen different configurations measured are shown in Table 1. Note that, when the detector is against the bottom of the CT at a cold trap-detector distance of 0 cm, the detector is between the collimator shutters; therefore, the tungsten collimator must be completely open to 11 cm in width.

Table 1. FGMS configurations – cold-trap-to-detector distance and collimator shutter width.

Trap-Det. Distance	Collimator Width		Trap-Det. Distance	Collimator Width		Trap-Det. Distance	Collimator Width
0.0	11.0		3.1	11.0		6.2	11.0
			3.1	2.5		6.2	2.5
			3.1	2.0		6.2	2.0
All values are in centimeters			3.1	1.5		6.2	1.5
			3.1	1.0		6.2	1.0
			3.1	0.5		6.2	0.5

To simulate the actual fission products released from fuel particles in the Fuel Accident Condition Simulator (FACS) furnace, the furnace was first heated to 1600°C. Then a certified gas standard source was injected into it. The source was injected using a pure helium sweep gas, which flowed through the source container carrying the source to the furnace. The helium then flowed through the furnace, through tubing, and passed through the CT, where the source froze out. The freezing points for the nuclide involved are xenon (-112°C), krypton (-157°C), and helium (-272°C), and nitrogen is liquid between -210°C and -196°C. Liquid nitrogen is cold enough to freeze xenon and krypton, but not helium. The helium flow continued to the facility exhaust. The counts per second (CPS) recorded by the detector were monitored, and, when the CPS plateaued, the transfer was deemed complete. Once the source was completely transferred to the CT, the valves to the CT were closed, and the CT was maintained at liquid nitrogen temperature until the efficiency measurements were complete. If the CT warms up at all, the source drifts, and efficiencies calculated from any future measurements would be inaccurate.

This document contains a summary of information recorded in two physical INL registered laboratory notebooks[2,3].

EXPERIMENTAL SETUP

The helium sweep gas that passes through the FACS furnace is routed through a particulate filter before exiting the hot cell and being routed to the FGMS. The FGMS was designed to measure ^{85}Kr, ^{133}Xe, and other radioactive fission gases released from the fuel. The FGMS consists of two independent measurement systems. Each system contains a charcoal CT, shielding, a collimator, and a high-purity germanium detector (HPGe). Figure 1 shows a schematic of the FGMS. FGMS #1 refers to the primary system into which the fission gas first flows and is then captured in Cold Trap #1 (CT#1), and HPGe detector P1 monitors CT#1 for gamma rays emitted from the sources. FGMS #2 refers to the secondary system containing Cold Trap #2 (CT#2), which is monitored by HPGe detector P2. Helium from the FACS furnace can be routed to either system or through first one system and then the other. The normal operation configuration is when the helium flows through CT#1, then CT#2, and finally to facility exhaust. This configuration enables confirmation that the fission gas is completely captured in CT#1, through observation that none of the fission gas is detected in CT#2. This redundant system was primarily developed in case the primary CT failed due to saturation, being plugged from impurities, or detector failure. In any case, helium flow could be routed to the second CT without interrupting the FACS experiment. Also, if the primary system fails, any radioactive sample can be transferred to the secondary system.

Additionally, a replaceable supplemental trap, referred to as a U-trap, may be placed right before the facility exhaust. This supplemental trap may be used to capture the source or sample for future use.

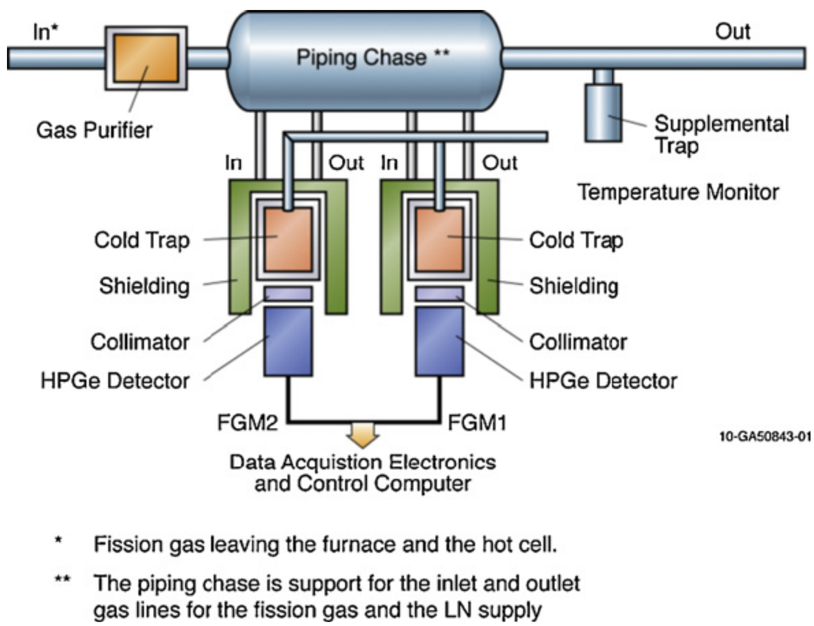

Figure 1. Schematic diagram of the Fission Gas Monitoring System.

Figure 2 shows an FGMS assembly. The assembly consists of an upper and lower lead (Pb) shield, HPGe detector, tungsten shutter system, and CT. A 10% closed-end coaxial HPGe detector with an upward-looking cryostat configuration is mounted on an adjustable lift cart. The detector cryostat is inserted into the lower Pb shield (4-cm thick), is positioned using machined spacers, and is then locked into place. Figure 3 shows a bird’s-eye view of the lower Pb shield, which runs the length of the detector’s crystal, even at the lowest position. The detector can be manually positioned by lowering the cart to detector-CT distances of 0 cm, 3.1 cm, or 6.2 cm. These are the distance between the top of the detector’s cryostat aluminum cover and the bottom of the CT. The detector will be lowered away from the CT if the detector’s deadtime becomes too high (> ~25%). In addition to lowering the detector, a shutter system (i.e., collimator) is available to reduce the count rate of the detector. Figure 3 shows the collimator shutters completely open (i.e., 11 cm wide). The collimator shutters are 3.1-cm thick and made of tungsten. When the detector-CT distance is at 3.1 or 6.2 cm, the automatic shutter system engages. If the detector's CPS reaches an adjustable threshold level, the collimator shutters automatically close to a preset width, preventing the detector's deadtime from becoming too high to record accurate data, while still enabling the detector to continue data collection. To avoid damage to the detector, this feature disengages when the detector is at the 0-cm position, putting it between the collimator shutters. The collimator shutter's allowed opening widths are 0.5, 1.0, 1.5, 2.0, 2.5, and 11.0 cm. Table 1 lists the thirteen detector distance-collimator configurations for which efficiency measurements were obtained.

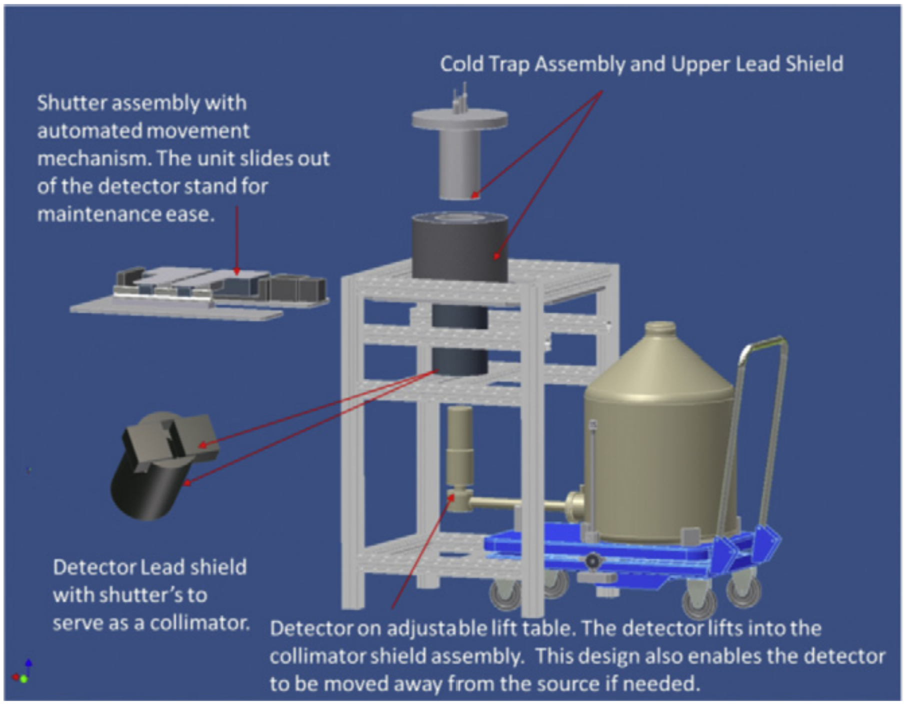

Figure 2. A cold trap and detector assembly for the Fission Gas Monitoring System.

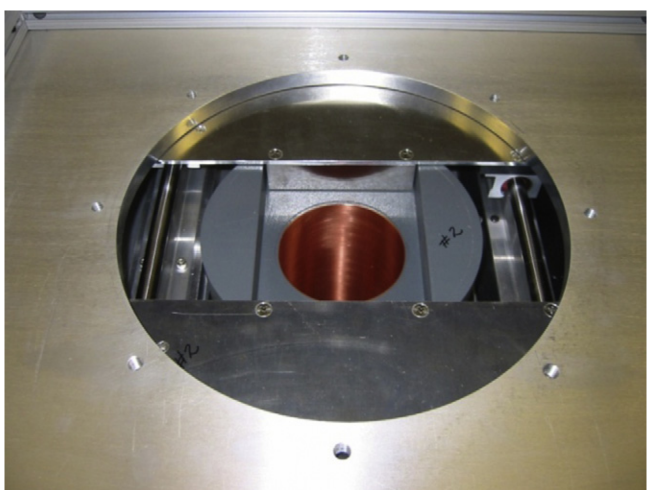

Figure 3. Automated tungsten collimator located between the cold trap assembly (above) and the high-purity germanium detector (below). The lower lead shield is shown, lined with a layer of tin and copper.

SOURCE TRANSFER

Five certified gas standard sources (see Appendix C) were purchased to obtain the system efficiency of the FGMS. Two ^{133}Xe sources (22.6 μCi and 212.8 μCi) and three ^{85}Kr sources (0.924 μCi, 103.95 μCi, and 390.8 μCi) were used. Two helium flow rates, 0.5 liters per minute (L/m) for testing in the Fuel Conditioning Facility (FCF) and 1.0 L/m for testing in the Hot Fuel Examination Facility (HFEF), were used. Both direct loading of the CT from the FACS and indirect loading from the other CT were tested. Table 1 shows all FGMS configurations for which efficiency measurements were made. Table 2 shows a summary of the parameters for the efficiency measurements. Figure 4 shows one of the 33-mL glass spheres containing a ^{85}Kr standard calibration source used in system efficiency measurements.

Table 2. Summary of the parameters for the efficiency measurements (see Appendix A for FGMS tabular efficiency results).

Table	FGMS #	Helium Flow Rate	Location	Source	Loading
A-1	1	0.5 L/m	FCF	^{133}Xe (22.6 μCi)	Direct
A-2	2	0.5 L/m	FCF	^{133}Xe (212.8 μCi)	Direct
A-3	1	0.5 L/m	FCF	^{85}Kr (0.924 μCi)	Direct
A-4	2	0.5 L/m	FCF	^{85}Kr (103.95 μCi)	Direct
A-5	1	1 L/m	HFEF	^{85}Kr (390.8 μCi)	Direct
A-6	2	1 L/m	HFEF	^{85}Kr (390.8 μCi)	Indirect
A-7	1	1 L/m	HFEF	^{85}Kr (390.8 μCi)	Indirect
A-8	2	1 L/m	Deduction		Direct

Figure 4. 33-mL glass sphere containing a ^{85}Kr standard 1.2-μCi source.

To simulate an actual FACS furnace experiment during which fuel specimens in the furnace release fission products, the furnace was first heated to 1600°C. Then, helium was flowed from outside the hot cell through a glass sphere containing the gas source standard and then injected into the FACS furnace. The helium flowed through the tantalum flow tube and exited out the exhaust at the top of the furnace. The helium was then routed through polished stainless-steel tubing out of the hot cell and over to the FGMS. The helium flow entered the bottom of the FGMS primary CT through the charcoal and exited the top, where it was routed through the secondary CT and, eventually, to facility exhaust.

Figure 5 shows a cross-section of the CT assembly and the upper Pb shielding. A liquid nitrogen reservoir surrounds the inner vessel which contains charcoal. The charcoal is held in place by a retaining screen with a 50% coverage mesh. The helium sweep gas is inserted toward the bottom of the trap, below the charcoal-retaining screen. The helium flows through the mesh, through the charcoal, and exits the top of the vessel. The helium must be maintained at a constant flow so the source will freeze out in the CT in a consistent manner. Different flow rates may result in different system efficiencies. During the initial efficiency measurements in FCF, the helium flow was kept at a rate of 0.5 L/m. Later, a helium flow rate of 1.0 L/m was established for experiments to be performed at HFEF. Therefore, all efficiency calibrations at FCF had a helium flow rate of 0.5 L/m, and all efficiency calibrations at HFEF had a helium flow rate of 1.0 L/m. Figure 6 shows the CPS measured by FGMS #1's detector (P1) and FGMS #2's detector (P2) during the transfer of the gas standard ^{85}Kr (390.81 μCi) source into CT#1 with a helium flow rate of 1.0 L/m. Note that there was no indication any part of the ^{85}Kr source made it to the secondary trap; the entire source was captured in the primary cold trap.

For transfer of the ^{85}Kr (390.81 μCi) source, the helium flow was started at 12:18 through the source sphere and into the furnace. Unfortunately, data collection did not begin until 12:23. In a previous test, it only took about 3 minutes for part of the source to travel through the FACS furnace to FGMS CT#1. The entire source transfer took approximately 30 minutes. After about 90 minutes, the helium flow was stopped, and CT#1 was sealed off. Most of the fission gas is believed to freeze to the bottom of the retaining screen, and the rest goes through the screen and freezes onto the charcoal very close to the retaining screen. The more fission gas that goes up into the charcoal, the lower the measured efficiency. Once the CT was sealed off, efficiency measurements were made for various configurations, as shown in Table 1. Multiple measurements were made for each configuration.

To study the difference between transferring a source directly from the FACS furnace to a CT and transferring from one CT to another, the ^{85}Kr (390.81 μCi) source was transferred from CT#1 to CT#2. This also saved the cost of another source. Table 3 shows the timeline of the transfer. Figure 7 shows the CPS measured by P1 and P2 during the transfer into CT#2 with a helium flow rate of 1.0 L/m. Note that the CPS measured by P2 is higher than that measured by P1; this results from different efficiencies between the two traps, possibly caused by differences in CT construction, detector efficiencies, and/or transfer methods. Figure 8 shows the CPS measured by P1 compared to the temperature of the CT during the transfer with a helium flow rate of 1.0 L/m. Note that the transfer did not start until the CT temperature reached the freezing point of krypton (-157°C). The gradual decline in CPS was due to the krypton working its way through the charcoal and eventually exiting the CT. After P2 begins recording an increase in CPS, indicating the source has started to freeze out, the entire source was transferred in about 12 minutes. The sharp increase in temperature at about 10:38 occurs when monitoring of the temperature was switched from the heater tube thermocouple (TC) to the charcoal TC. The heater tube is further down in the CT and gives a more accurate reading than the charcoal TC. The switch is made because a heater is placed in the tube to increase the speed of the transfer and make sure the entire source is released.

Figure 9 shows the CPS measured by P1 and P2 during the transfer from CT#2 back to CT#1. Figure 10 shows the CPS measured by P2 compared to the temperature of the CT during transfer. Figure 11 shows the CPS measured by P1 during transfer from CT#1 into a supplemental trap (U-trap) for storage.

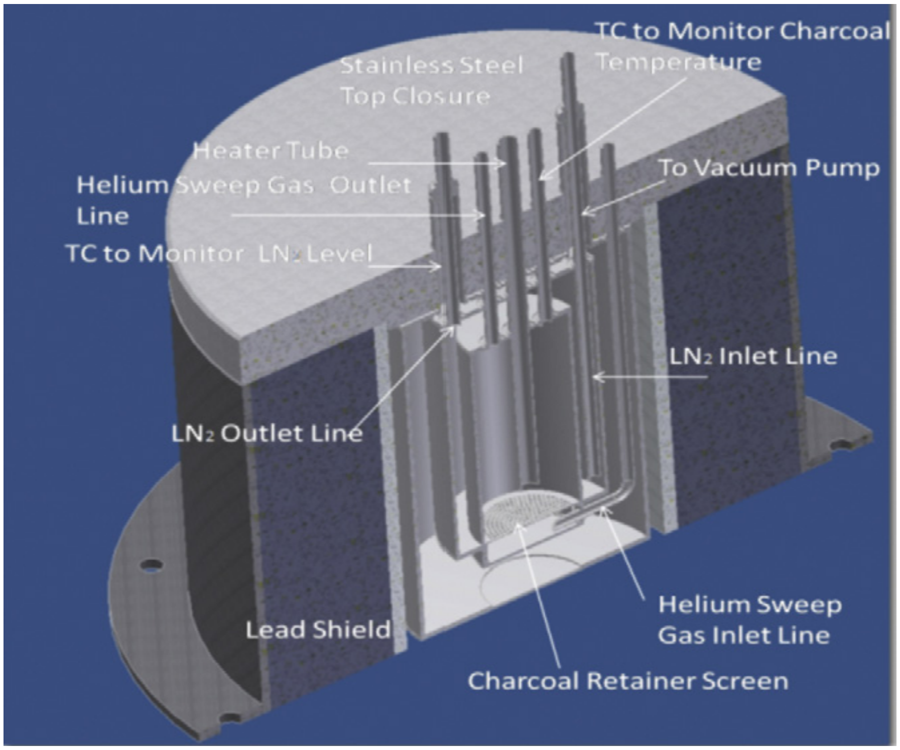

Figure 5. Cross-section of the cold trap assembly and surrounding lead shielding.

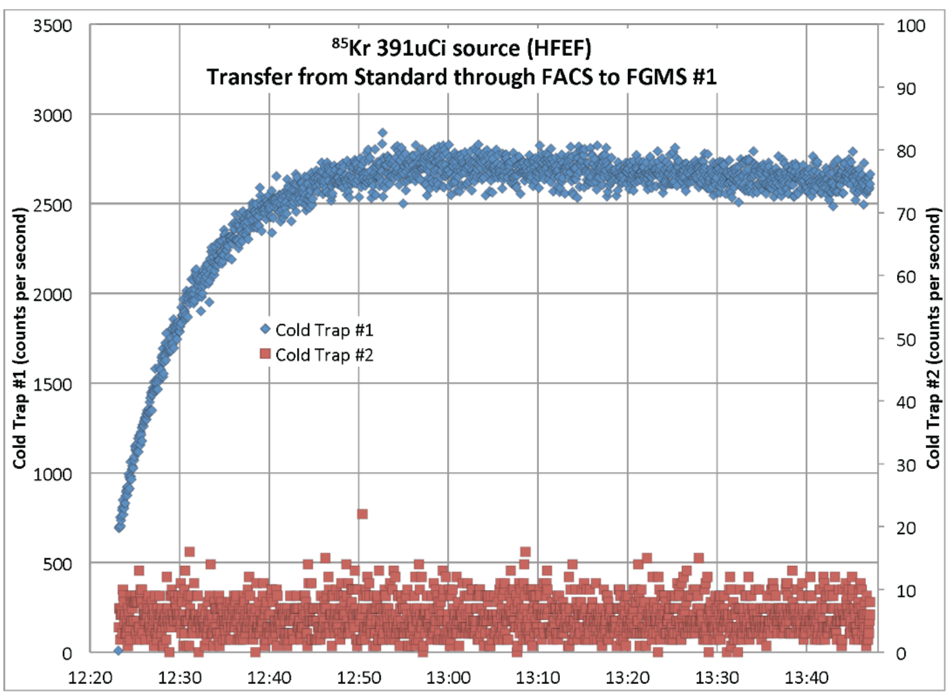

Figure 6. Standard ^{85}Kr source transfer through the FACS furnace to CT#1 (HFEF), using a flow of 1.0 L/m of helium. Performed on November 1, 2011. Table A-5 contains the efficiency results calculated from data collected after this transfer.

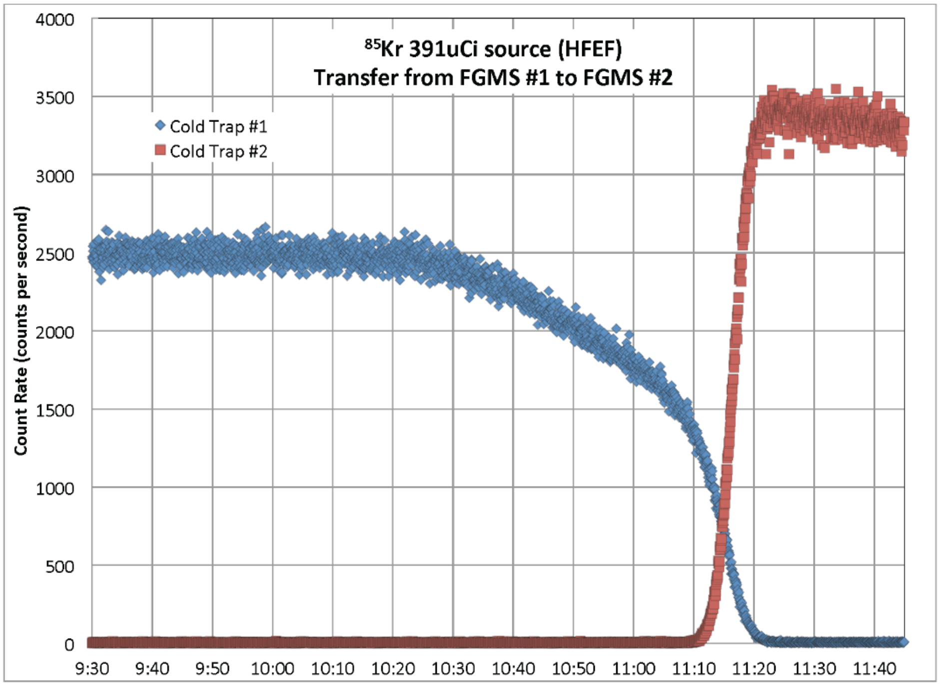

Figure 7. Standard ^{85}Kr source transfer from CT#1 to CT#2 (HFEF), using a flow of 1.0 L/m of helium.

Table 3. Timeline of ^{85}Kr (390.81 μCi) source transfer from CT#1 to CT#2.

Time	Elapsed Time	Status of ^{85}Kr (390.81 μCi) Source Transfer from CT#1 to CT#2
9:24		Finished filling CT#1 with liquid nitrogen and stopped liquid nitrogen autofill
9:32		Started helium flow through CT#1 and CT#2
10:26	0:00	Started to see decrease in CPS in CT#1
10:38	0:12	Switched TC in CT#1 from heater tube to charcoal
10:43	0:17	Turned on heater in CT#1 to 200°F
11:10	0:44	Started to see counts in CT#2
11:22	0:56	Source entirely transferred to CT#2
11:45	1:19	Sealed CT#2 and stopped data acquisition

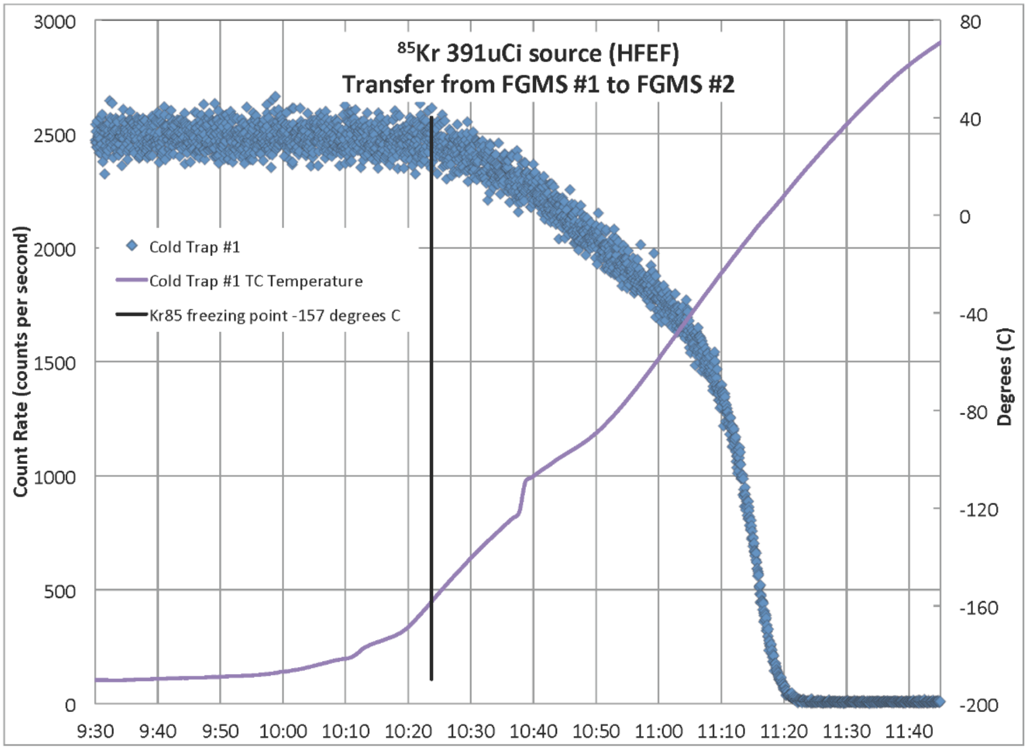

Figure 8. Transfer of the ^{85}Kr source out of CT#1, along with the temperature of the #1 heater tube, using a flow of 1.0 L/m of helium.

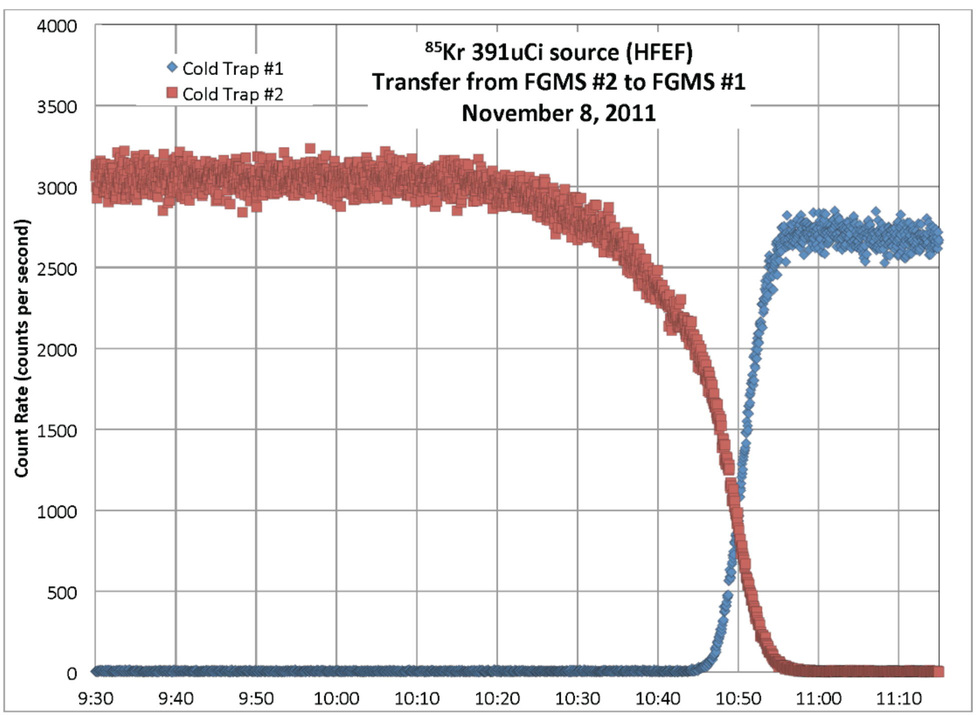

Figure 9. Standard ^{85}Kr source transfer from CT#2 back to CT#1 (HFEF) using a flow of 1.0 L/m of helium.

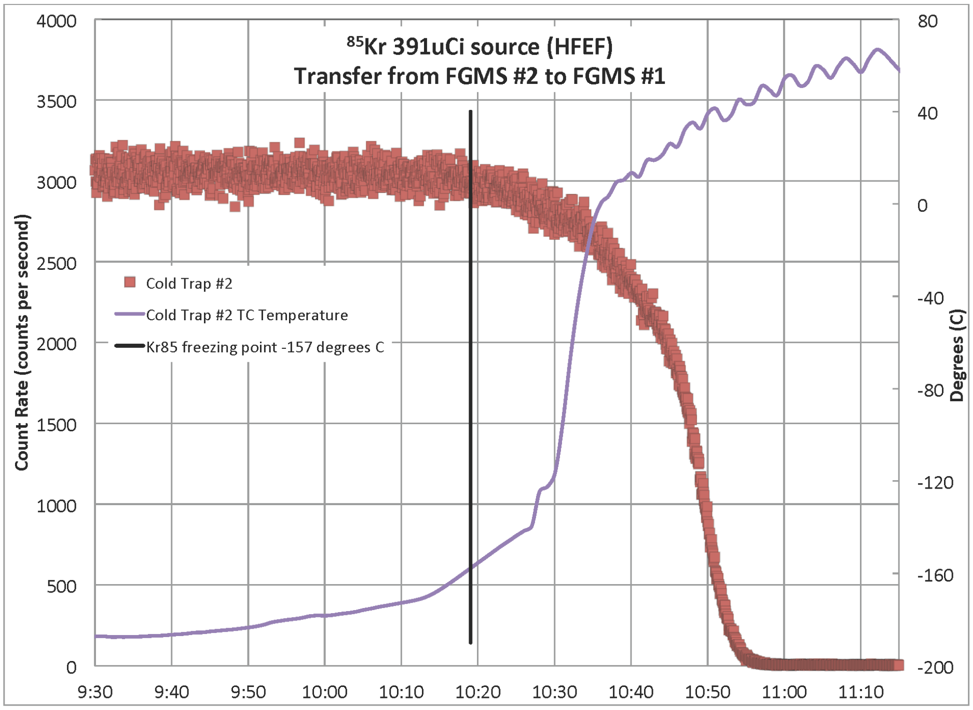

Figure 10. Transfer of the ^{85}Kr source out of CT#2, along with the temperature of the #2 heater tube.

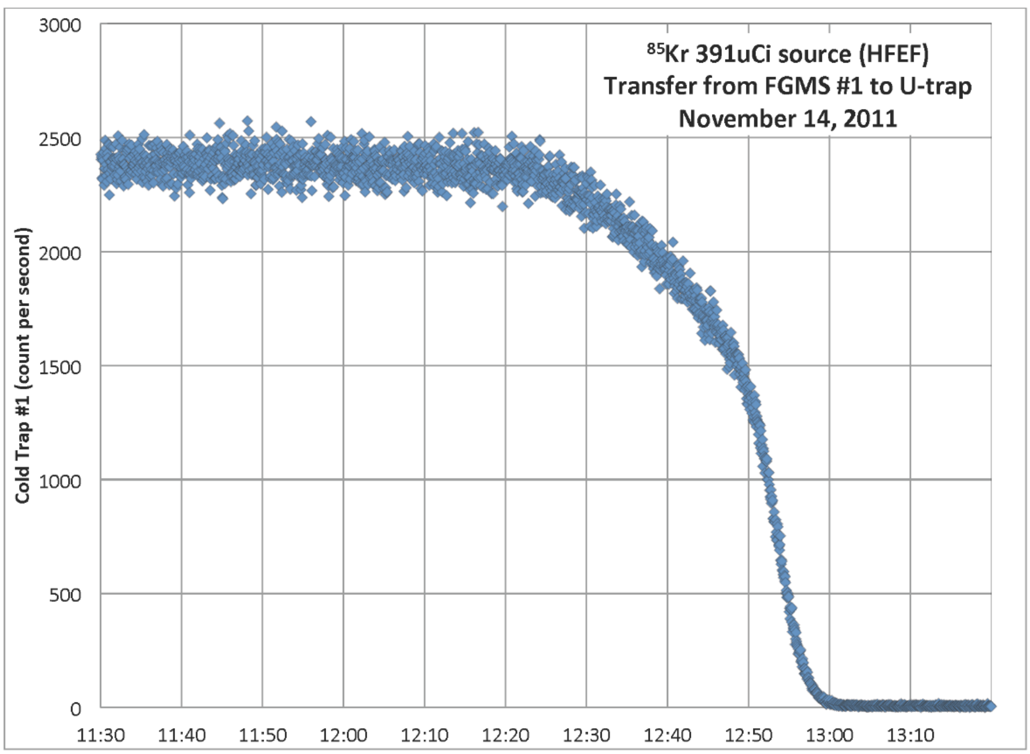

Figure 11. Standard ^{85}Kr source transfer from CT#1 to a U-trap (HFEF), using a flow of 1.0 L/m of helium.

EFFICIENCY MEASUREMENT AND COMPARISON

Ideally, to get the most accurate system efficiency, one would mimic as closely as possible the parameters to be used in the actual experiment. In addition, it is necessary to use a certified gas standard source with the same isotopic makeup as the isotopes of interest. In this case, ^{133}Xe and ^{85}Kr are the isotopes of interest, emitting gamma rays of 81 keV and 514 keV, respectively.

The most accurate way to mimic failing of fuel in the FACS furnace is to inject the certified source into the FACS furnace at temperature and directly load the CT. If the primary CT fails, it would be necessary to transfer the contents to the secondary trap. Therefore, transferring the certified source from CT#1 to CT#2 was also performed to record the efficiency. This was done to study whether there is any difference in the efficiencies between loading the CT directly from the FACS and from the other CT.

Once measurements of a source are complete, the peak area of the gamma ray of interest is determined. But knowing the live time, real time, peak area, emission probability, and half-lives, and by using the formulas in Appendix B, the efficiency can be calculated.

Figure 12 and Figure 13 show a comparison of the efficiency measurements of the two flow rates for FGMS #1 and #2, respectively. As expected, the 1.0-L/m efficiency measurements were lower than the 0.5-L/m rate. The higher helium flow rate allows less time for fission gas to freeze out on the retaining screen before going into the charcoal. As can be seen, efficiency measurements at a detector-CT distance of 0 cm show the greatest separation. This indicates an extended source (i.e., the more one moves away from an extended source, the less the source geometry affects the efficiency measurements, and the more it appears to be a point source). That being said, one has to consider whether the large difference in the two source activities affected the results. To address this, a comparison is made between the ratios of the efficiencies of P2 5.740E-3 (103.95 μCi, 0.5L/m) and 5.145E-3 (390.81 μCi, 1L/m), 1.12, and P1 4.686E-3 (0.924 μCi, 0.5L/m) and 4.050E-3 (390.81 μCi, 1L/m), 1.16. These two ratios (1.12 and 1.16) are very similar and suggest that using different amounts of Kr85 does not affect the efficiencies.

Figure 14 shows a comparison between direct loading of CT#1 and indirect loading of CT#1 from CT#2. Source transfer from CT#2 to CT#1 results in a slightly higher efficiency than when the source is loaded directly from the FACS furnace.

A direct loading of CT#2 for ^{85}Kr with a helium flow rate of 1L/m was never measured. Because of this, the efficiency was estimated using the indirect loading of CT#2 and a gain factor obtained from the ratio of indirect versus direct loading of CT#1. FGMS #2 is a backup system not intended to be the primary trap directly loaded from the FACS furnace.

Efficiency measurements using ^{133}Xe were not taken with a helium flow rate of 1L/m. ^{133}Xe (81 keV) should not be present unless the fuel is re-irradiated. If this is going to occur, an efficiency measurement must be made.

Data for some of the collimator shutter widths are missing due to liquid nitrogen filling problems, which caused the cold traps to warm up and make the data unreliable. This occurred after the important detector-CT distances and collimator widths were finished. The likelihood of needing the missing data is extremely low, and the expense of obtaining the measurements is high. Therefore, it was decided not to make those measurements.

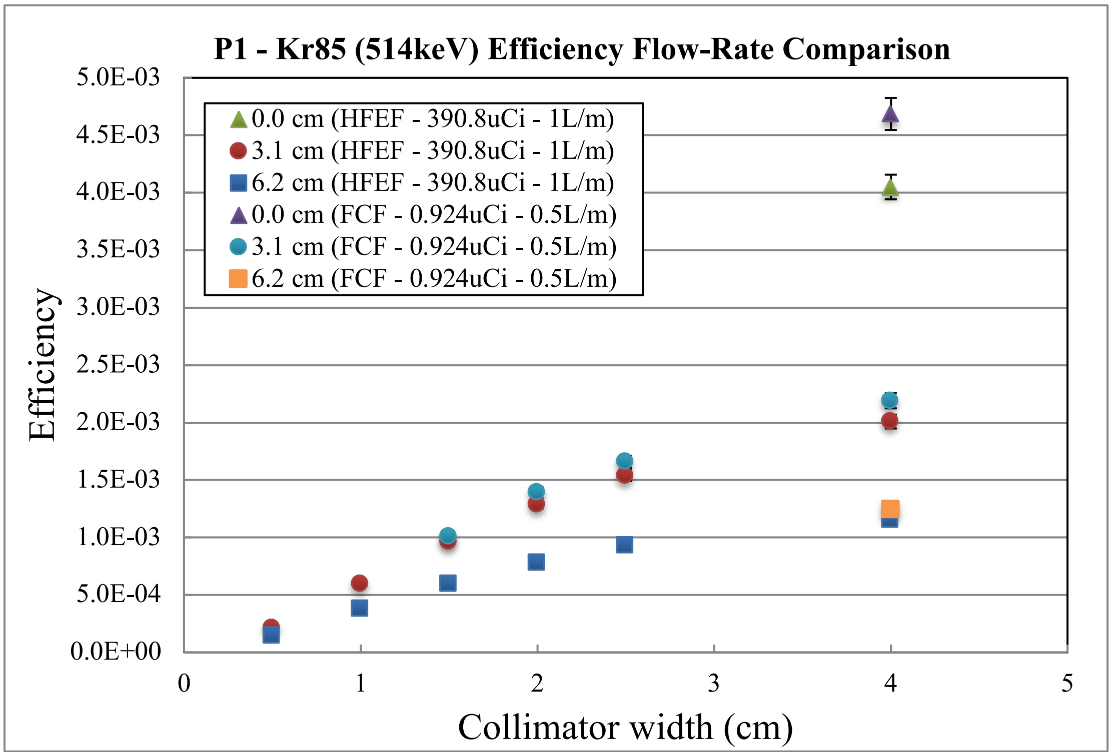

Figure 12. FGMS #1 efficiency flow-rate comparison of 0.5L/m versus 1L/m with direct loading of the cold traps. Data from Table A-3 and Table A-5 were used to generate this plot. For display purposes, the collimator shutter width of 11 cm is shown as 4 cm on the plot.

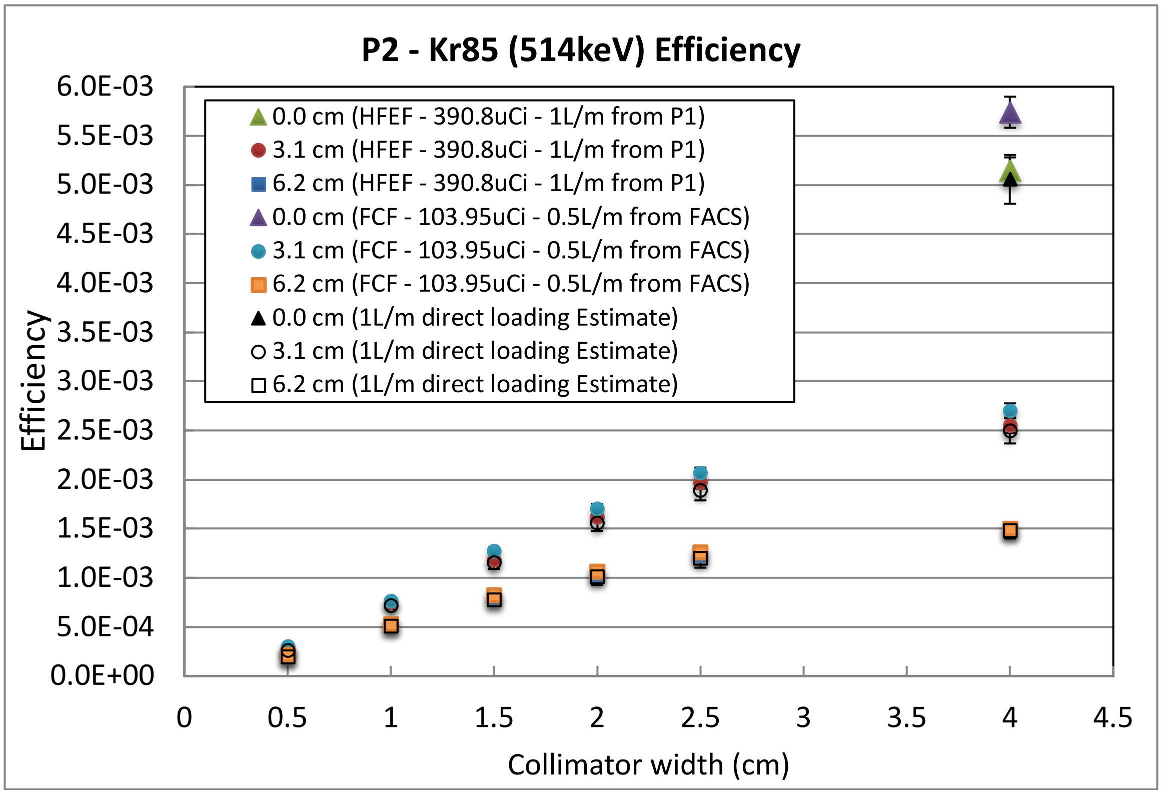

Figure 13. FGMS #2 efficiency flow-rate comparison and estimations. Data from Table A-4, Table A-6, and Table A-8 were used to generate this plot. For display purposes, the collimator shutter width of 11 cm is shown as 4 cm on the plot.

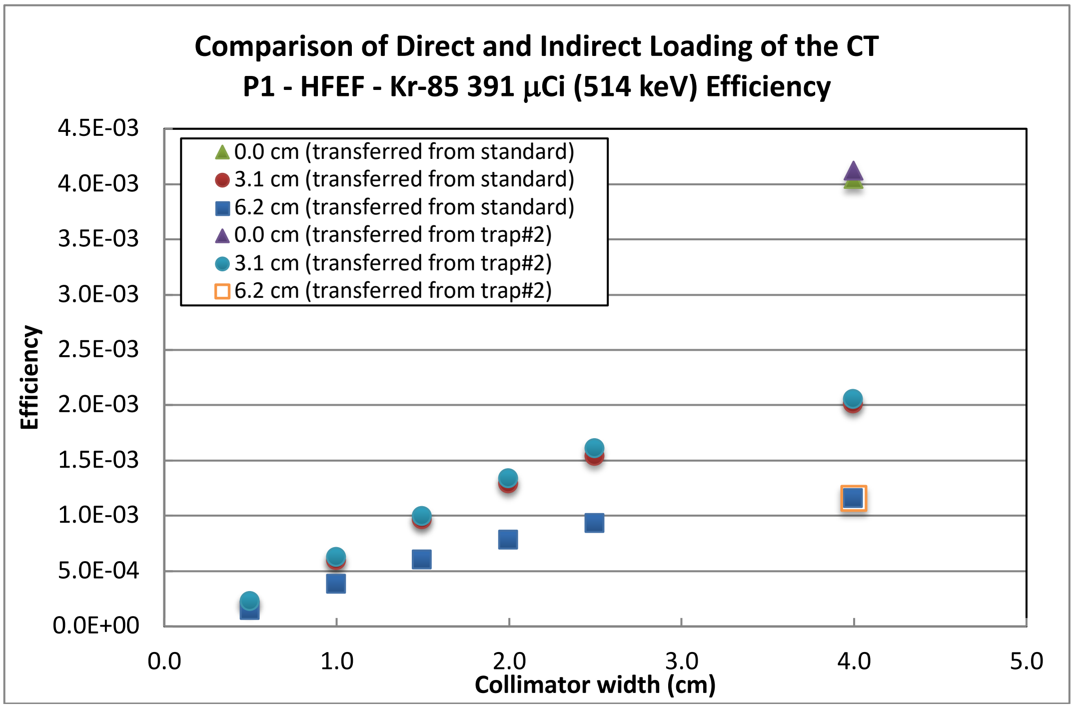

Figure 14. FGMS #1 comparison of direct loading and transfer from the other cold trap (1.0 L/m). Data from Table A-5 and Table A-7 were used to generate this plot. For display purposes, the collimator shutter width of 11 cm is shown as 4 cm on the plot.

SUMMARY

The FGMS was calibrated with five certified standards, ranging from 0.924 to 390.8 μCi. This range of activity simulated prospective AGR-1 fuel failure within the FACS furnace, ranging from a simulated inventory of one failed particle to many failed particles. HPGe detector responses were obtained at three different detector-to-trap differences (i.e., height), with the corresponding collimation shutter width ranging from 0.5 to 11.0 cm. An efficiency calibration curve was generated for each configuration. These measurements enabled the FGMS team to quantify the activity of the fission gas captured within the FGMS CTs.

Efficiency measurements were acquired from December 2009 to November 2011 and performed at FCF (mockup shop) and HFEF. The FGMS now permanently resides at HFEF. Efficiency measurements were performed during this extended time span because of certified standard availability, budget constraints, facility shutdowns, and other parameters outside the FGMS support team’s control.

Measurements provided in this report satisfy the requirements for the AGR-1 fuel post-irradiation examination experiment series. It is recommended that periodic efficiency measurements are performed to ensure that increased usage of the cold traps does not affect their efficiencies.

ACRONYMS

AGR	Advanced Gas Reactor
CT	cold trap
CPS	counts per second
FACS	Fuel Accident Condition Simulator Furnace
FCF	Fuel Conditioning Facility (located in the Materials Fuels Complex at the Idaho National Laboratory)
FGMS	Fission Gas Monitoring System
HFEF	Hot Fuel Examination Facility (located in the Materials Fuels Complex at the Idaho National Laboratory)
HPGe	high-purity germanium
Kr	krypton
L/m	liters per minute
Pb	lead
P1	HPGe detector used in FGMS #1 to monitor CT#1
P2	HPGe detector used in FGMS #2 to monitor CT#2
TC	thermocouple
Xe	xenon

REFERENCES

1. Debertin, Klaus, and Richard Helmer. 1988. “Efficiency calibration and emission-rate determinations.” In *Gamma- and X-ray Spectrometry with Semiconductor Detectors*. 205-289. Amsterdam: Elsevier Science B.V.

2. AGR-1 PIE FGMS #1, LAB-1194, Idaho National Laboratory.

3. AGR PIE FGMS #2, LAB-1602, Idaho National Laboratory.

Appendix A

FGMS Tabular Efficiency Results

^{133}Xe (81.0 keV, 5.243 Days Half-Life) Efficiency: FCF Mockup, 0.5 L/m Helium Flow

Table A-1. FGMS #1 efficiency measurements using ^{133}Xe (22.57 μCi, 80860-370) source transferred using a helium flow of 0.5 L/m (FCF) directly to CT#1. A systematic uncertainty of 2% was added to the statistical uncertainty.

Distance	Collimator (cm)	Efficiency	Uncertainty	Measurements	1st Data Taken	Last Data Taken
0	11.0	3.258E-03	2.0%	5	12/01/09	12/01/09
3.1	11.0	1.617E-03	2.0%	5	12/01/09	12/01/09
3.1	2.5	1.151E-03	2.0%	5	12/01/09	12/01/09
3.1	2.0	9.131E-04	2.0%	5	12/01/09	12/01/09
3.1	1.5	6.383E-04	2.0%	5	12/01/09	12/01/09
3.1	1.0	3.459E-04	2.0%	5	12/01/09	12/01/09
3.1	0.5	9.383E-05	2.0%	5	12/01/09	12/01/09
6.2	11.0	9.058E-04	2.0%	5	11/30/09	11/30/09
6.2	2.5	6.786E-04	2.0%	5	12/01/09	12/01/09
6.2	2.0	5.259E-04	2.0%	5	12/04/09	12/05/09
6.2	1.5	3.807E-04	2.0%	5	12/05/09	12/06/09
6.2	1.0	2.220E-04	2.0%	5	12/03/09	12/03/09
6.2	0.5	6.686E-05	2.0%	5	12/03/09	12/03/09

Table A-2. FGMS #2 efficiency measurements using ^{133}Xe (212.76 μCi, 80861-370) source transferred using a helium flow of 0.5 L/m (FCF) directly to CT#2. A systematic uncertainty of 2% was added to the statistical uncertainty.

Distance	Collimator (cm)	Efficiency	Uncertainty	Measurements	1st Data Taken	Last Data Taken
0	11.0	3.734E-03	2.0%	15	12/14/09	12/16/09
3.1	11.0	1.795E-03	2.0%	15	12/14/09	12/16/09
3.1	2.5	1.236E-03	2.0%	5	12/14/09	12/14/09
3.1	2.0	9.945E-04	2.0%	5	12/15/09	12/15/09
3.1	1.5	7.482E-04	2.0%	5	12/15/09	12/15/09
3.1	1.0	4.284E-04	2.0%	5	12/15/09	12/15/09
3.1	0.5	1.467E-04	2.0%	5	12/15/09	12/15/09
6.2	11.0	1.018E-03	2.0%	15	12/14/09	12/16/09
6.2	2.5	7.719E-04	2.0%	5	12/14/09	12/14/09
6.2	2.0	6.591E-04	2.0%	5	12/15/09	12/15/09
6.2	1.5	5.043E-04	2.0%	5	12/15/09	12/15/09
6.2	1.0	2.944E-04	2.0%	5	12/15/09	12/16/09
6.2	0.5	8.172E-05	2.0%	5	12/14/09	12/14/09

^{85}Kr (514.0 keV, 10.756 Years Half-Life [YHL]) Efficiency Fuel Conditioning Facility

Table A-3. FGMS #1 efficiency measurements using ^{85}Kr (0.924 μCi, 80511-370) source transferred using a helium flow of 0.5 L/m (FCF) directly to CT#1. A systematic uncertainty of 2% was added to the statistical uncertainty.

Distance	Collimator (cm)	Efficiency	Uncertainty	Measurements	1st Data Taken	Last Data Taken
0	11.0	4.686E-03	3.0%	5	04/15/10	04/16/10
3.1	11.0	2.191E-03	3.1%	5	04/16/10	04/18/10
3.1	2.5	1.659E-03	3.1%	5	05/04/10	05/08/10
3.1	2.0	1.393E-03	3.4%	4	04/28/10	04/29/10
3.1	1.5	1.012E-03	3.6%	4	04/30/10	05/03/10
6.2	11.0	1.245E-03	3.4%	3	04/19/10	04/20/10

Table A-4. FGMS #2 efficiency measurements using ^{85}Kr (103.95 μCi, 80513-370) source transferred using a helium flow of 0.5 L/m (FCF) directly to CT#2. A systematic uncertainty of 2% was added to the statistical uncertainty.

Distance	Collimator (cm)	Efficiency	Uncertainty	Measurements	1st Data Taken	Last Data Taken
0	11.0	5.740E-03	2.8%	6	06/15/10	06/15/10
3.1	11.0	2.700E-03	2.8%	5	06/16/10	06/16/10
3.1	2.5	2.064E-03	2.9%	5	06/16/10	06/16/10
3.1	2.0	1.704E-03	2.9%	5	06/16/10	06/16/10
3.1	1.5	1.273E-03	2.9%	5	06/16/10	06/16/10
3.1	1.0	7.646E-04	2.7%	10	06/21/10	06/24/10
3.1	0.5	2.981E-04	2.9%	5	06/16/10	06/17/10
6.2	11.0	1.502E-03	2.6%	9	06/21/10	06/24/10
6.2	2.5	1.258E-03	2.8%	5	06/22/10	06/22/10
6.2	2.0	1.060E-03	2.7%	7	06/22/10	06/24/10
6.2	1.5	8.210E-04	2.8%	5	06/22/10	06/23/10

6.2	1.0	5.288E-04	2.8%	5	06/21/10	06/22/10
6.2	0.5	2.130E-04	2.8%	6	06/17/10	06/18/10

FGMS Efficiency Results (HFEF, 1.0 L/m Helium Flow)

^{85}Kr (514.0 keV, 10.756 Years Half-Life [YHL]) Efficiency

Table A-5. FGMS #1 efficiency measurements using ^{85}Kr (390.81 μCi, 80514-370) source through the FACS furnace at 1600°C transferred using a helium flow of 1.0 L/m (HFEF) directly to CT#1. A systematic uncertainty of 2% was added to the statistical uncertainty.

Distance	Collimator (cm)	Efficiency	Uncertainty	Measurements	1st Data Taken	Last Data Taken
0	11.0	4.050E-03	2.7%	9	11/01/11	11/03/11
3.1	11.0	2.009E-03	3.0%	3	11/01/11	11/01/11
3.1	2.5	1.539E-03	3.0%	3	11/01/11	11/01/11
3.1	2.0	1.288E-03	3.0%	3	11/02/11	11/02/11
3.1	1.5	9.673E-04	3.1%	3	11/02/11	11/02/11
3.1	1.0	5.961E-04	3.1%	3	11/03/11	11/03/11
3.1	0.5	2.113E-04	3.0%	3	11/02/11	11/02/11
6.2	11.0	1.156E-03	3.1%	3	11/02/11	11/02/11
6.2	2.5	9.311E-04	3.0%	3	11/02/11	11/02/11
6.2	2.0	7.818E-04	3.1%	3	11/02/11	11/02/11
6.2	1.5	5.977E-04	3.1%	3	11/03/11	11/03/11
6.2	1.0	3.783E-04	3.1%	3	11/02/11	11/02/11
6.2	0.5	1.459E-04	3.0%	3	11/01/11	11/01/11

Table A-6. FGMS #2 efficiency measurements using ^{85}Kr (390.81 μCi, 80514-370) source transferred from the FGMS CT#1 (indirect) using a helium flow of 1.0 L/m (HFEF). A systematic uncertainty of 2% was added to the statistical uncertainty.

Distance	Collimator (cm)	Efficiency	Uncertainty	Measure-ments	First Data Taken	Last Data Taken

0	11.0	5.145E-03	2.6%	9	11/07/11	11/08/11
3.1	11.0	2.551E-03	3.0%	3	11/07/11	11/07/11
3.1	2.5	1.970E-03	3.1%	3	11/07/11	11/07/11
3.1	2.0	1.616E-03	3.1%	3	11/07/11	11/07/11
3.1	1.5	1.182E-03	3.1%	3	11/08/11	11/08/11
3.1	1.0	7.527E-04	3.1%	3	11/07/11	11/07/11
3.1	0.5	2.773E-04	3.1%	3	11/08/11	11/08/11
6.2	11.0	1.484E-03	3.1%	3	11/07/11	11/07/11
6.2	2.5	1.224E-03	3.3%	2	11/07/11	11/07/11
6.2	2.0	1.028E-03	3.1%	3	11/08/11	11/08/11
6.2	1.5	7.922E-04	3.1%	3	11/08/11	11/08/11
6.2	1.0	5.187E-04	3.1%	3	11/07/11	11/07/11
6.2	0.5	2.017E-04	3.1%	3	11/08/11	11/08/11

Table A-7. FGMS #1 efficiency measurements using ^{85}Kr (390.81 μCi, 80514-370) source transferred back from the FGMS CT#2 (indirect) using a helium flow of 1.0 L/m (HFEF). A systematic uncertainty of 2% was added to the statistical uncertainty.

Distance	Collimator (cm)	Efficiency	Uncertainty	Measure-ments	First Data Taken	Last Data Taken	Gain-Transfer from CT#2 vs. from FACS
0	11.0	4.121E-03	3.2%	3	11/09/11	11/09/11	1.8%
3.1	11.0	2.050E-03	3.1%	3	11/09/11	11/09/11	2.0%
3.1	2.5	1.605E-03	3.1%	3	11/09/11	11/09/11	4.3%
3.1	2.0	1.334E-03	3.1%	3	11/09/11	11/09/11	3.6%
3.1	1.5	9.931E-04	3.1%	3	11/09/11	11/09/11	2.7%
3.1	1.0	6.238E-04	3.2%	3	11/09/11	11/09/11	4.7%
3.1	0.5	2.263E-04	3.9%	1	11/09/11	11/09/11	7.1%
6.2	11.0	1.160E-03	3.0%	3	11/09/11	11/09/11	0.4%

Estimation of FGMS #2 ^{85}Kr Efficiency

Table A-8. Estimating ^{85}Kr efficiency for FGMS #2 using the source transfer from FGMS#1 (Table A-7) and the gain from FGMS#1 to estimate a direct transfer.

Distance	Collimator (cm)	Efficiency	Uncertainty	Gain from Table A-7

0	11.0	5.057E-03	4.9%	1.8%
3.1	11.0	2.500E-03	5.3%	2.0%
3.1	2.5	1.889E-03	5.3%	4.3%
3.1	2.0	1.560E-03	5.3%	3.6%
3.1	1.5	1.152E-03	5.3%	2.7%
3.1	1.0	7.193E-04	5.4%	4.7%
3.1	0.5	2.590E-04	5.9%	7.1%
6.2	11.0	1.479E-03	5.3%	0.4%
6.2	2.5	1.200E-03	8.0%	2.0%
6.2	2.0	1.008E-03	8.0%	2.0%
6.2	1.5	7.766E-04	8.0%	2.0%
6.2	1.0	5.085E-04	8.0%	2.0%
6.2	0.5	1.977E-04	8.0%	2.0%

Appendix B
Calculation of Efficiency and Its Uncertainty[1]

From the activity equation:

$$\boldsymbol{Activity(Bq)_{T_{ref}} = \frac{n_{T_{ref}}}{\varepsilon * p}}$$

Efficiency (ε):

$$\boldsymbol{\varepsilon = \frac{n_{T_{ref}}}{Activity(Bq)_{T_{ref}} * p} = \frac{n_{TOC} * \ DC}{Activity(Bq)_{T_{ref}} * p}}$$

where

$\boldsymbol{n_{T_{ref}}}$ is the count per second at the reference date.

$$\boldsymbol{n_{TOC}} = \frac{Area}{LT}$$

Area = fitted peak area (number of gamma rays detected)

LT = live time (seconds)

p for ^{133}Xe (81 keV) emission probability is 38.0%.

p for ^{85}Kr (514 keV) emission probability is 0.434%.

DC is the decay correction:

$$DC = \frac{\lambda * RT}{\exp(-\lambda * \Delta T) - \exp\,[-\lambda * (\Delta T + RT)]}$$

where

$$\lambda = \frac{\ln{(2)}}{t_{1/2}}$$

$t_{1/2}$= NIST half-life for ^{133}Xe is 5.2474 +/- 0.0005 days — converted to seconds

$t_{1/2}$= NIST half-life for ^{85}Kr is 10.752 +/- 0.01 years — converted to seconds

RT = real time (seconds)

ΔT = Time in seconds from acquisition time to T_{ref}

$$\sigma_{\varepsilon} = \varepsilon * \sqrt{\frac{\sigma_{Area}^2}{Area^2} + \frac{\sigma_{DC}^2}{DC^2} + \frac{\sigma_{Act_{T_{ref}}(dpm)}^2}{Act_{T_{ref}}(dpm)^2}}$$

where

$$\sigma_{Area} = uncertainty\ in\ fit\ area, including\ the\ Poisson\ counting$$

$$\sigma_{Act_{T_{ref}}(dpm)} = uncertainty\ in\ Activity$$

$$\sigma_{DC}^2 = \frac{1}{t_{1/2}} * [\ln(2) * \Delta T]^2 * \sigma_{t_{1/2}}^2$$

where

$$\sigma_{t_{1/2}}(^{133}Xe) = 43.2\ seconds$$

$$\sigma_{t_{1/2}}(^{85}Kr) = 3.156E5\ seconds$$

Appendix C
Radionuclide Source Certificate of Calibration

Eckert & Ziegler
Analytics

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Tel 404•352•8677
Fax 404•352•2837
www.analyticsinc.com

CERTIFICATE OF CALIBRATION
Standard Radionuclide Source

80860-370

Xe-133 Gas Standard in 33 mL Glass Sphere

Customer: INL/Battelle Energy Alliance, LLC (DOE)
P.O. No.: 00092178, Item 1 (0000166052 4)

This standard radionuclide source was calibrated by comparison to NIST traceable standards in the same geometry using a germanium gamma spectrometer system. This standard was examined for interfering gamma ray emitting impurities using a germanium gamma spectrometer system. At the time of calibration no interfering gamma emmitting impurities could be detected. Eckert & Ziegler Analytics (EZA) maintains traceability to the National Institute of Standards and Technology through a Measurements Assurance Program as described in USNRC Regulatory Guide 4.15, Revision 1, February, 1979, and compliance with ANSI N42.22-1995, "Traceability of Radioactive Sources to NIST." EZA is accredited by the Health Physics Society (HPS) for the production of NIST-traceable sources, and this source was produced in accordance with the HPS accreditation requirements. Customers may report any concerns with the accreditation program to the HPS Secretariat, 1313 Dolley Madison Blvd., Ste. 402, McLean, VA 22101.

Calibration Date: November 17, 2009 12:00 EST

Isotope	Activity (Bq)	Half-Life	Uncertainty Type (%) u_A	u_B	U
Xe-133	8.361E+05	5.243 days	0.04	1.70	3.40

Uncertainty: U – Relative expanded uncertainty, k=2. See NIST Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results."

Comments:
Total volume of sphere 2095 including septum side arm is 32.38 cc.

Source Calibrated By: ______________
J. D. McCorvey, Count Room Supervisor

QA Approved: ______________ Date: 11-16-09
D. M. Montgomery, QA Manager

End of Certificate

Figure C-1. Certificate of calibration for ^{133}Xe (22.57 μCi) used at FCF.

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CERTIFICATE OF CALIBRATION

Standard Radionuclide Source

80861-370

Xe-133 Gas Standard in 33 mL Glass Sphere

Customer: INL/Battelle Energy Alliance, LLC (DOE)
P.O. No.: 00092178, Item 2 (0000166053 4)

This standard radionuclide source was calibrated with an ionization chamber that was calibrated by the National Physical Laboratory, Teddington, U.K., and is directly traceable to national standards. Eckert & Ziegler Analytics (EZA) maintains traceability to the National Institute of Standards and Technology through a Measurements Assurance Program as described in USNRC Regulatory Guide 4.15, Revision 1, February, 1979, and compliance with ANSI N42.22-1995, "Traceability of Radioactive Sources to NIST." EZA is accredited by the Health Physics Society (HPS) for the production of NIST-traceable sources, and this source was produced in accordance with the HPS accreditation requirements. Customers may report any concerns with the accreditation program to the HPS Secretariat, 1313 Dolley Madison Blvd., Ste. 402, McLean, VA 22101.

Calibration Date: November 17, 2009 12:00 EST

Isotope	Activity (Bq)	Half-Life	Uncertainty Type (%) u_A	u_B	U
Xe-133	7.880E+06	5.243 days	0.06	1.50	3.00

Uncertainty: U – Relative expanded uncertainty, k=2. See NIST Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results."

Comments:
Total volume of sphere 3129 including septum side arm is 32.16 cc.

Source Calibrated By: ______________________
E. A. Taskaev, Production Manager

QA Approved: ______________________ QA ALT Date: 11/17/09
D. M. Montgomery, QA Manager

End of Certificate

Figure C-2. Certificate of calibration for ^{133}Xe (212.76 μCi) used at FCF.

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CERTIFICATE OF CALIBRATION

Standard Radionuclide Source

80511-370

Kr-85 Gas Standard in 33 mL Glass Sphere

Customer: INL/Battelle Energy Alliance (DOE)
P.O. No.: 00089165 Rev 1, Item 1 (0000165218 4)

This standard radionuclide source was calibrated by comparison to NIST traceable standards in the same geometry using a germanium gamma spectrometer system. This standard was examined for interfering gamma ray emitting impurities using a germanium gamma spectrometer system. At the time of calibration no interfering gamma emmitting impurities could be detected. Eckert & Ziegler Analytics (EZA) maintains traceability to the National Institute of Standards and Technology through a Measurements Assurance Program as described in USNRC Regulatory Guide 4.15, Revision 1, February, 1979, and compliance with ANSI N42.22-1995, "Traceability of Radioactive Sources to NIST." EZA is accredited by the Health Physics Society (HPS) for the production of NIST-traceable sources, and this source was produced in accordance with the HPS accreditation requirements. Customers may report any concerns with the accreditation program to the HPS Secretariat, 1313 Dolley Madison Blvd., Ste. 402, McLean, VA 22101.

Calibration Date: September 23, 2009 12:00 PM EST

Isotope	Activity (Bq)	Half-Life	Uncertainty*, (%) Type u_A	u_B	U
Kr-85	3.418E+04	10.752 years	0.28	1.7	3.4

***Uncertainty:** U – Relative expanded uncertainty, k=2. See NIST Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results."

Comments:
Total volume of sphere 1376 including septum side arm is 32.41 cc.

Source Calibrated By: [signature]
J. D. McCorvey, Count Room Supervisor

QA Approved: [signature]
D. M. Montgomery, QA Manager

Date: 9-23-09

End of Certificate

Corporate Office

Figure C-3. Certificate of calibration for ^{85}Kr (0.924 μCi) used at FCF.

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CERTIFICATE OF CALIBRATION

Standard Radionuclide Source

80512-370

Kr-85 Gas Standard in 33 mL Glass Sphere

Customer: INL/Battelle Energy Alliance (DOE)
P.O. No.: 00089165 Rev 1, Item 2 (0000165220 4)

This standard radionuclide source was calibrated by comparison to NIST traceable standards in the same geometry using a germanium gamma spectrometer system. This standard was examined for interfering gamma ray emitting impurities using a germanium gamma spectrometer system. At the time of calibration no interfering gamma emmitting impurities could be detected. Eckert & Ziegler Analytics (EZA) maintains traceability to the National Institute of Standards and Technology through a Measurements Assurance Program as described in USNRC Regulatory Guide 4.15, Revision 1, February, 1979, and compliance with ANSI N42.22-1995, "Traceability of Radioactive Sources to NIST." EZA is accredited by the Health Physics Society (HPS) for the production of NIST-traceable sources, and this source was produced in accordance with the HPS accreditation requirements. Customers may report any concerns with the accreditation program to the HPS Secretariat, 1313 Dolley Madison Blvd., Ste. 402, McLean, VA 22101.

Calibration Date: September 23, 2009 12:00 PM EST

Isotope	Activity (Bq)	Half-Life	Uncertainty*, (%) Type u_A	u_B	U
Kr-85	3.819E+05	10.752 years	1.0	1.7	3.9

***Uncertainty:** U – Relative expanded uncertainty, k=2. See NIST Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results."

Comments:
Total volume of sphere 1361 including septum side arm is 32.14 cc.

Source Calibrated By: [signature]
J. D. McCorvey, Count Room Supervisor

QA Approved: [signature]
D. M. Montgomery, QA Manager

Date: 9-23-09

ACCREDITED SOURCE CALIBRATION LABORATORY — HEALTH PHYSICS SOCIETY — FOUNDED 1956

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Figure C-4. Certificate of Calibration for ^{85}Kr (about 10 μCi) used at FCF.

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CERTIFICATE OF CALIBRATION
Standard Radionuclide Source

80513-370

Kr-85 Gas Standard in 33 mL Glass Sphere

Customer: INL/Battelle Energy Alliance (DOE)
P.O. No.: 00089165 Rev 1, Item 3 (0000165221 4)

This standard radionuclide source was calibrated by comparison to NIST traceable standards in the same geometry using a germanium gamma spectrometer system. This standard was examined for interfering gamma ray emitting impurities using a germanium gamma spectrometer system. At the time of calibration no interfering gamma emmitting impurities could be detected. Eckert & Ziegler Analytics (EZA) maintains traceability to the National Institute of Standards and Technology through a Measurements Assurance Program as described in USNRC Regulatory Guide 4.15, Revision 1, February, 1979, and compliance with ANSI N42.22-1995, "Traceability of Radioactive Sources to NIST." EZA is accredited by the Health Physics Society (HPS) for the production of NIST-traceable sources, and this source was produced in accordance with the HPS accreditation requirements. Customers may report any concerns with the accreditation program to the HPS Secretariat, 1313 Dolley Madison Blvd., Ste. 402, McLean, VA 22101.

Calibration Date: September 23, 2009 12:00 PM EST

			Uncertainty*, (%)		
			Type		
Isotope	Activity (Bq)	Half-Life	u_A	u_B	U
Kr-85	3.846E+06	10.752 years	1.4	1.7	5.6

***Uncertainty:** U – Relative expanded uncertainty, k=2. See NIST Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results."

Comments:
Total volume of sphere 3022 including septum side arm is 30.24 cc.

Source Calibrated By: ______________________
J. D. McCorvey, Count Room Supervisor

QA Approved: ______________________ Date: 9-23-09
D. M. Montgomery, QA Manager

End of Certificate

Figure C-5. Certificate of calibration for ^{85}Kr (103.95 μCi) used at FCF.

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Analytics

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Atlanta, Georgia 30318
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Fax 404•352•2837
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CERTIFICATE OF CALIBRATION

Standard Radionuclide Source

80514-370

Kr-85 Gas Standard in 33 mL Glass Sphere

Customer: INL/Battelle Energy Alliance (DOE)
P.O. No.: 00089165 Rev 1, Item 4 (0000165222 4)

This standard radionuclide source was calibrated by comparison to NIST traceable standards in the same geometry using a germanium gamma spectrometer system. This standard was examined for interfering gamma ray emitting impurities using a germanium gamma spectrometer system. At the time of calibration no interfering gamma emmitting impurities could be detected. Eckert & Ziegler Analytics (EZA) maintains traceability to the National Institute of Standards and Technology through a Measurements Assurance Program as described in USNRC Regulatory Guide 4.15, Revision 1, February, 1979, and compliance with ANSI N42.22-1995, "Traceability of Radioactive Sources to NIST." EZA is accredited by the Health Physics Society (HPS) for the production of NIST-traceable sources, and this source was produced in accordance with the HPS accreditation requirements. Customers may report any concerns with the accreditation program to the HPS Secretariat, 1313 Dolley Madison Blvd., Ste. 402, McLean, VA 22101.

Calibration Date: September 23, 2009 12:00 PM EST

Isotope	Activity (Bq)	Half-Life	Uncertainty*, (%) Type u_A	u_B	U
Kr-85	1.446E+07	10.752 years	0.5	1.7	4.9

***Uncertainty:** U – Relative expanded uncertainty, k=2. See NIST Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results."

Comments:
Total volume of sphere 2660 including septum side arm is 32.50 cc.

Source Calibrated By: ______________
J. D. McCorvey, Count Room Supervisor

QA Approved: ______________ Date: 9-23-09
D. M. Montgomery, QA Manager

End of Certificate

Figure C-6. Certificate of calibration for ^{85}Kr (390.81 μCi) used at HFEF.