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LLNL-TR-2011217

Lawrence Livermore National Laboratory

Production of NBL PO plutonium isotopic standards CRM 136A, CRM 137A, and CRM 138A

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November 2025

Disclaimer

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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August 25, 2025

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Acknowledgements

We are grateful to the New Brunswick Laboratory Program Office (NBL PO) for their support. We thank Kyle Samperton (now at Savannah River National Laboratory) for his contributions to early testing and planning. We thank Kelsey Woody and Sarah Hansen (LLNL) for assistance cleaning new FEP and PFA vessels. We thank the LLNL operations management, Facilities, Environmental Safety and Health (ES&H), Radiological and Hazardous Waste Management, and Materials Management teams for helping to facilitate the necessary material transfers, work controls, and waste requisitions.

Overview

Production of Pu isotopic standards

Lawrence Livermore National Laboratory (LLNL) produced approximately 1 mg units of purified Pu from the parent New Brunswick Laboratory (NBL) certified reference materials (CRM) 137, 136 and 138 isotopic standards for the NBL Program Office (NBL PO) as detailed in the revised project plan [1]. As stated in the plan, three representative units of each material were dispensed at the same time to be characterized at LLNL and provide informational values for the quantity of Pu and progeny nuclides in each unit. NBL PO intends to collect and evaluate isotopic measurement data from multiple laboratories and certify these materials as new isotopic standards C137A, C136A, and C138A, respectively. Soon after production eleven units of each analytical standard were shipped to other analytical laboratories for the certification effort, and 121, 119, and 119 units of C137A, C136A and C138A, respectively were shipped to Mickey Finch at Y12 NBL distribution center in November 2024 (30-gallon drum, TID 003777 PRL 7000005043). Residual purified Pu from the effort is being stored indefinitely in B332 at LLNL. Detailed methods can be found in the production plan, and this report describes and documents aspects of the production effort that are not in or were modified from the original production plan.

Project plan revisions

During the production effort for CRM 137A, which was the first of the three to be completed, several minor changes had to be made to the signed project plan, which are all captured in the revised project plan [1]. These changes and the reasons for them are summarized in Table 1. The subsequent production of CRM 136A and CRM 138A proceeded according to the revised plan.

Table 1. Changes made to the original project plan during C137A production.

Section and page	*Change*	*Reason for change*
p. 1 Project Team and roles	Added J. Wimpenny	Josh Wimpenny took over as lead mass spectrometrist when Ross Williams retired.
p 1, p 6 C.a.	Omit addition of $NaNO_2$ prior to first column	Sulfate stabilizes Pu(IV) and there is so much sulfate we did not want to add additional salts
p 6 B.p.	Deleted step p	Don't need additional conc. HNO_3 because we did not add $NaNO_2$
p 6 B. k-m	Added 0.001 M HF to 8 M HNO_3	The material is difficult to dissolve; trace HF can aid dissolution
p. 6 B.l.	Added note that solution can be recycled to transfer slurry. This means transferring the slurry	There is very little dissolution at room temperature, so transferring the slurry is a larger effort than anticipated. We found recycling the solution an effective way to transfer all material without dramatically increasing the volume.

	to the new vial, then after particles settle in the new vial pipetting some solution from the new vial and dispensing in the old vial to create more slurry for transfer to the new vial.	
p. 6 B.m.	Changed the minimum amount of solution from 4.0 mL to 8.0 mL	Based on the solubility of Pu sulfate in 8 M HNO_3 8 mL may be the minimum amount required. The sulfate concentration is dictated by the total volume and loading 8 mL did result in a yield >98% so it will be best to use a volume close to this.
p. 6 B.o.	Check every hour instead of 15 minutes	The material took ~ 7 hours to dissolve at 50 degrees, so checking every 15 minutes is not necessary.
p. 6-7 C.d.	Changed approximately 9 mL to between 0.5 and 9 mL	Although liquid completely covering the jar bottom is ~9 mL, the dark solution was still visible as a small spot in the middle of the jar. It is difficult to tell the difference before opening it, and if it doesn't go completely dry there is no problem.
p. 7 C.h.	Change 10^4 to 10^5 Bq	Fixing a previous calculation error. The intention was 0.01% of the starting ^{241}Am activity, which is 10^5 Bq for C137A.
p. 7 D.a.	Added, "The diluted solution is allowed to equilibrate overnight."	May help ensure aliquots are withdrawn from homogenous solution.
p. 7 D.b.	Removed step B that prescribes weighing of master solution bottle	Weighing the bottle passed out of the glovebox is impractical and is not necessary. The aliquots are dispensed volumetrically so the total weight is not needed. The massic concentration is determined by IDMS in hold point 3, but the density of the solution was estimated accurately enough to plan aliquot dispensing.
p. 7 D.c. (b)	Added details of collecting an analytical aliquot for gravimetric concentration measurements in hold point 3.	Original volumetric aliquoting plan had too high uncertainty for hold point 3. We found that collecting aliquots that were weighed and diluted for ID-MS worked well.
p. 8 D.g. (f)	Changed 16 mL to 9-10 mL, added	The inner diameter of the tubing is smaller than what was used to calculate the dead volume of

	comment about using hand-held meter	the tubing. After 3 times dispensing 1.6 mL the meter showed that the outlet solution was active. Three additional 1.6 mL units were dispensed for good measure prior to dispensing units.
p. 8 D.k. (j)	added "at least" before 110, changed the numbers by one unit for aliquots Y and Z	It was later noted that no Pu was dispensed into bottle 31 during C137A production, so all subsequent bottles were re-numbered, shifting down by 1 unit. We verified that all other bottles had equal amounts of activity.
p. 9 D.n. (m) and o.(n)	Added "After two additional clean surveys ES&H surveillance in between batches will no longer be required."	Our HP team did not find it necessary to continue doing surveys in between each batch and no contamination events occurred.
p. 9 D.p. (o)	Added "transferred back to the 240 mL jar"	Savillex does not make caps for the 500 mL bottles with fittings to connect to the impingers.
p. 9 F.a.	Changed 1034 to 1033	Typo in original
p. 9 G a. and b.	Added information about shipping analytical units and the logistics of temporarily storing the others.	After going through it with C137A we have a better understanding of the process and thought it would be helpful to have more detail in the plan.
p. 14 Gamma Spectrometry	Removed paragraph describing the counting of a volumetric sub-aliquot.	Volumetric sub-aliquots had too high uncertainty to be useful due to the difficulty of estimating the total volume of Pu solution and the lack of precision pipettes. Low Am was verified via IDMS instead.
p. 16 Appendix E Measurement of Pu isotopic composition	Modified text to reflect that all isotopes including Pu-238 are measured by the Nu-Plasma HR	We realized the background U-238 is negligible in this case and the 238/239 can be accurately measured by MC-ICP-MS.*

* **Determination of the ^{238}U blank on ^{238}Pu**

Determining the ^{238}U interference on ^{238}Pu was not straightforward given that the majority is likely to have been environmental in origin. Uranium isotope dilution measurements of the purified plutonium showed that after the bulk separation the amount of ingrown uranium was small, and ingrown ^{238}U was expected to be negligible given the low abundances of ^{242}Pu and its relatively long half-life. The ^{238}U blank was quantified during the purification of uranium from bulk plutonium, but this is likely to be a significant overestimate of the blank associated with preparation of the

plutonium isotopic composition samples. This is likely for two reasons; i) between two and three column passes were required to obtain a high separation factor between uranium and plutonium for the UID measurement, whereas one pass was required for purification of plutonium, and ii) the UID purification procedure selects for uranium, whereas uranium is removed when purifying for plutonium. Nevertheless, here we have assumed that the plutonium purification also had a ^{238}U contribution of ~2 pg from environmental sources and have calculated the effect of this on the measured $^{238}Pu/^{239}Pu$ (see Table 1a below). In all cases, a 2pg ^{238}U blank from sample processing would not shift the measured $^{238}Pu/^{239}Pu$ outside the uncertainty of the measurement, even for CRM 138-A, which has a significantly lower abundance of ^{238}Pu. Because this blank contribution is likely to be a significant overestimate, we conclude that ^{238}U background is unlikely to have had any effect on the measured $^{238}Pu/^{239}Pu$ ratios.

Table 1a. Estimated maximum effect of ^{238}U blank on measured $^{238}Pu/^{239}Pu$ values.

	Mass of ^{238}Pu in 0.5ml (pg)	Fraction of ^{238}Pu from blank	Measured $^{238}Pu/^{239}Pu$ (x)	Std Uncert (1s)	Blank Corr. $^{238}Pu/^{239}Pu$ (y)	x-y	Outside of uncertainty ?
C136-A	13200	0.00015	0.0019837	0.0000024	0.0019834	0.00000030	No
C137-A	15858	0.00013	0.0026023	0.0000049	0.0026020	0.00000033	No
C138-A	603	0.00332	0.0000852	0.0000021	0.0000849	0.00000028	No

Timing

The dates of completion for major steps in Pu isotopic standard production are summarized in Table 2.

Table 2. Dates of completion for major steps in Pu isotopic standard production process.

Action	*Date of completion C137A*	*Date of completion C136A*	*Date of completion C138A*
Blank chemistry and evaporation run	5/20/2021	6/27/2022	11/6/2023
Received original CRM unit in B151 R1034	9/16/2021	6/22/2022	11/3/2023
Original CRM unit dissolved	9/20/2021	6/24/2022	11/6/2023
Purification chemistry complete	9/28/2021	6/29/2022	11/13/2023
Units dispensed	10/05/2021	7/15/2022	1/4/2024
Last batch of units evaporated	10/25/2021	8/17/2022	1/24/2024

Units shipped to LANL, PNNL, INL and ORNL	3/02/2022	3/21/2023	7/22/2024
Pu isotope dilution measurements of representative units	10/21/2021	7/21/2022	1/25/2024
U isotope dilution measurements of representative units	11/7/2021	9/6/2022	2/8/2024
Am isotope dilution measurements of representative units	11/15/2021	8/25/2022	2/7/2024
Np isotope dilution measurements of representative units	11/28/2021	12/19/2022	7/22/2024
Packaged units delivered to Y12	11/19/2024	11/19/2024	11/19/2024

Unpacking and dissolution of parent materials

Unpacking

CRM 137

The NBL C137 parent material was shipped from LANL to B332 at LLNL along with one unit each of NBL C136 and NBL C138 and received in May 2021. There the three materials were separated into individual items in LLNL's material control and accountability system, and each was physically packaged into a clean plastic bag and Al can prior to transferring the C137 unit to building 151 in September 2021. During the repackaging process the team in B332 noted alpha contamination on the outside of the original C137 packaging (shown in Figure 1). The package was opened in a glovebox in B151 R1034, which had never been used before and was where the materials were subsequently purified and dispensed.

Figure 1. C137 unit in primary packaging from LANL.

The glass vial, shown in Figure 2, was removed from the plastic bag, and placed in the Teflon petri dish. The glass seemed to be tinted brown, presumably from radiolytic damage, and the inner walls coated with plutonium sulfate. There seemed to be more material towards the top of the vial than the bottom. The words "C137 00141" was hand-written on a white label affixed to the vial.

Figure 2. C137 vial prior to opening.

The vial was carefully opened inside a plastic beaker in case of pressure differential or dispersible of material around the rim. No pressure differential or visible dispersion of material was observed. Part of the Teflon and cardboard cap liners remained on glass vial rim when the cap was unscrewed. The inside of the cap and uncapped vial care shown in Figure 3.

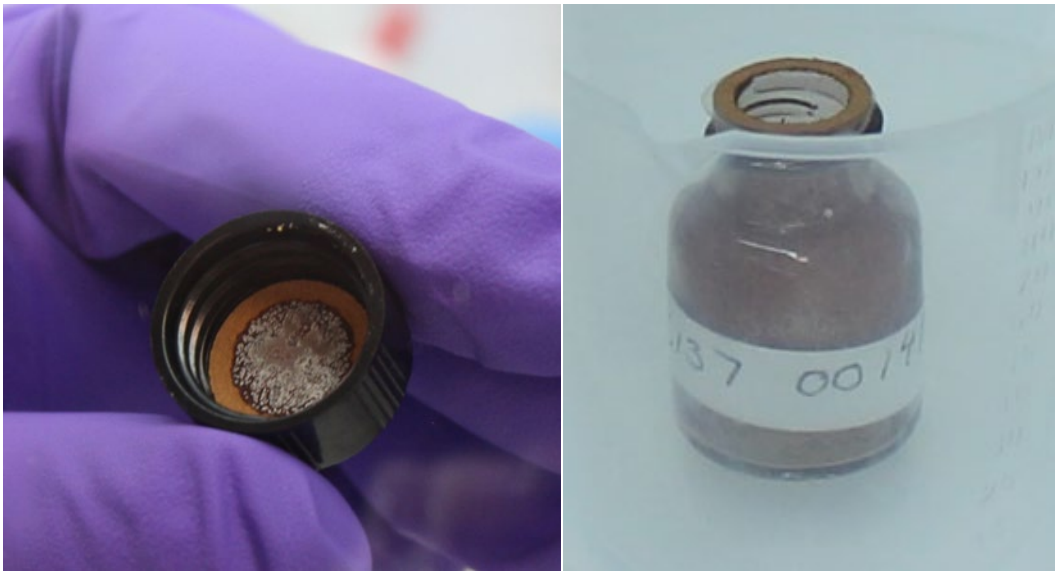


Figure 3. Inside of C137 vial cap (left) and uncapped vial sitting in a plastic beaker (right) upon opening.

CRM 136

The NBL C136 parent material was transferred to B151 from B332 at LLNL in June 2022 and opened inside the same glovebox in B151 R1034 after smear surveys confirmed that the inside of the glovebox was free of contamination. Smear survey results are included as Appendix A. The packaging from LANL is shown in Figure 4.

Figure 4. C136 unit in primary packaging from LANL.

The glass vial, shown in Figure 5, was similar in appearance to that of C137 except it had both an official NBL label and a secondary white label with the words “C136 00287” handwritten. The inside of the vial cap displayed similar patterns of radiolytic damage to that of C137 (Figure 3).

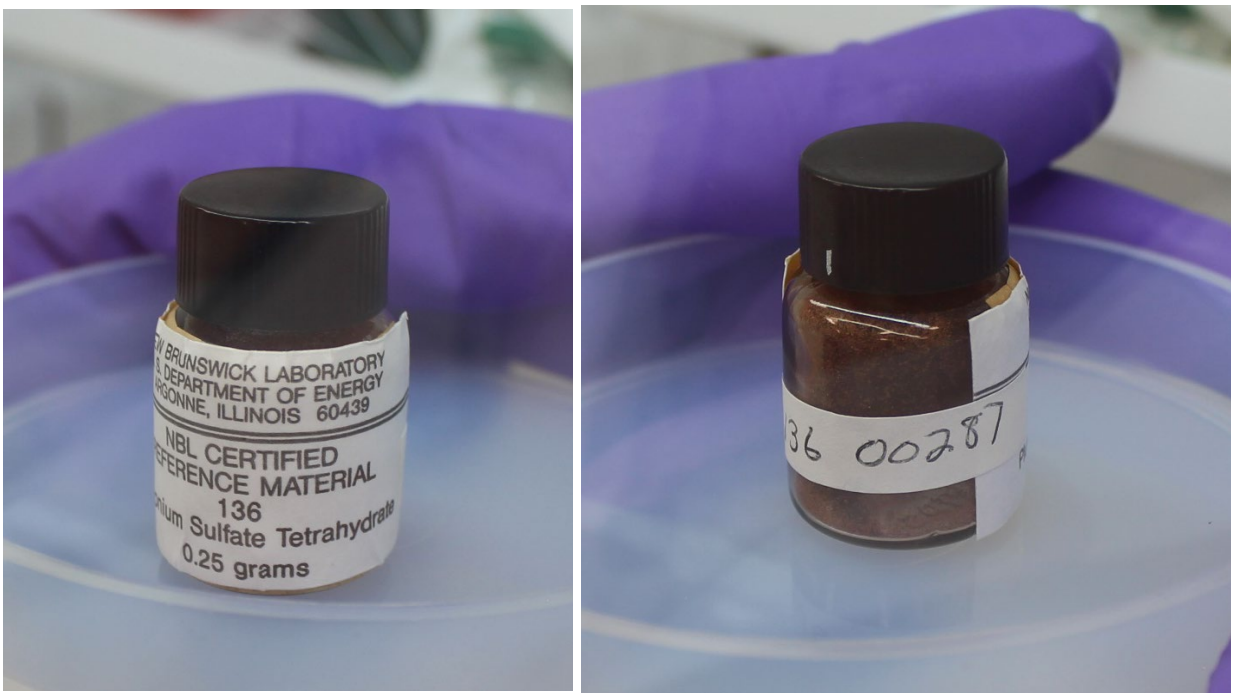


Figure 5. C136 vial prior to opening.

CRM 138

The NBL C138 parent material was transferred to B151 from B332 at LLNL in November 2023 and unpackaged in the same glovebox. The primary packaging for C138 is shown in Figure 6 and the vial prior to opening in Figure 7. In addition to the official NBL label the vial had a piece of masking tape affixed to it with “C-138-35 mg 53” handwritten on it. The top of the vial cap appeared to be contaminated with an unknown white substance.

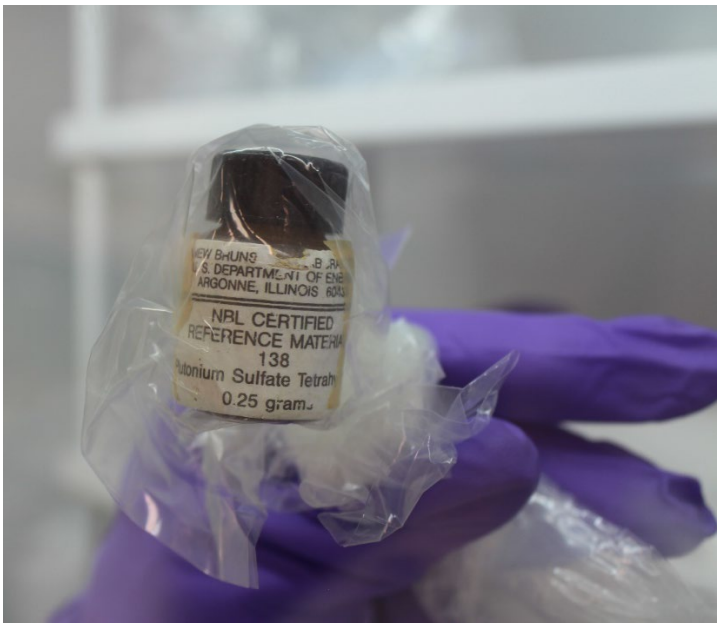


Figure 6. C138 unit in primary packaging from LANL.

Figure 7. C138 vial prior to opening.

Upon opening the vial, a lot of white material appeared around the vial opening and the cap also looked different than the other two, see Figure 8.

Figure 8. Inside of C138 vial cap (left) and uncapped vial (right) upon opening.

Dissolution

CRM 137

6 aliquots of 0.5 mL 8 M HNO_3 were rinsed around the inside of the vial, then vial sat at room temperature for 1 hour. The solution and particles in a slurry were transferred by pipette to a new clean 20 mL glass vial, and the old vial rinsed with 0.5 mL 8M HNO_3 into new vial four times. During the vial rinse the Teflon ring and cardboard that was stuck to the glass of the vial opening came off. The empty vial is shown in Figure 9, where it appears the color is inherent to the glass, presumably from radiation damage. The new vial was placed on a 50° hot plate for 2 hours and then sat at room temperature for 60 hours, with no visible change in the amount of undissolved solid. 3 mL 8 M HNO_3/0.0028 M HF was added, giving a total of 8 mL 8 M HNO_3/0.00105 M HF. After 5.5 hours on a 50° hot plate all the solid particles were dissolved, and the solution was dark brown. Figure 10 shows the undissolved solid in the new vial prior to adding HF and the dark brown solution after heating with trace HF.

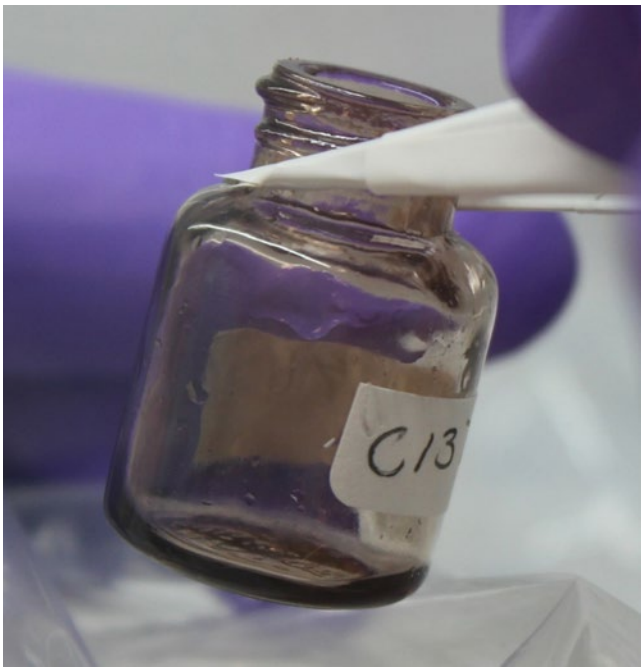


Figure 9. Empty glass vial that previously contained CRM 137 material.

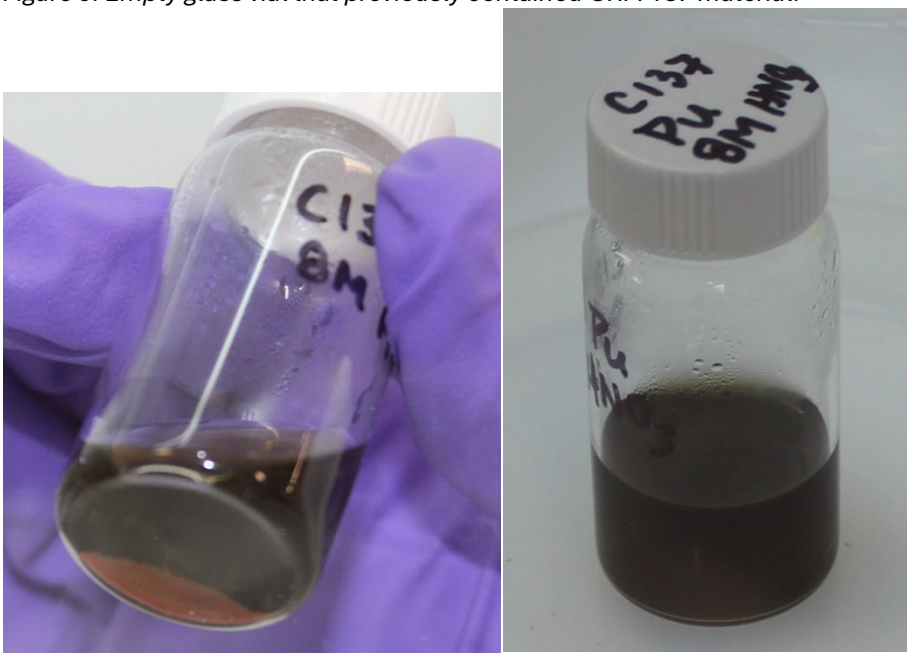


Figure 10. C137 material in a new glass vial, partially dissolved in nitric acid (left) and fully dissolved after addition of trace HF and gentle heating (right).

CRM 136

The Pu sulfate was transferred to a new vial as a slurry in a total of 4 mL 8 M HNO_3, then the old vial rinsed four times with 0.5 mL and two times with 1 mL 8 M HNO_3/0.0021 M HF to give a total concentration of 0.00105 M HF in the combined 8 M HNO_3 solution. The vial sat on a 50° hot plate for a total of 963 minutes over the course of 48 hours with the heat off during overnight times in between heating. It was noted that while the Pu sulfate fully dissolved, a few white fluffy solid particles floating on top of the solution persisted.

CRM 138

The Pu sulfate was transferred to a clean vial as a slurry and the vial rinsed similarly to C136 but with a total of 9 mL 8 M HNO_3/0.00105 M HF. Upon opening the C138 unit, and prior to dissolution, a lot of white material was observed inside the cap and the interior walls of the bottle (see Figure 8). This was only observed in the C138 bottle, not in the C137 bottle (Figure 9) or the C136 bottle, which was similar in appearance to the C137 bottle. To ensure complete transfer of the Pu, we did not attempt to exclude the white material from being transferred to the new vial. After transferring all Pu and rinsing the old vial, a lot of white residue remained on the sides of the old vial, see Figure 11. Inevitably much of the unidentified white contaminant transferred with the Pu sulfate to the new vial. After sitting on the 50° hot plate for 4121 minutes, the Pu was fully dissolved and most of the white material sat at the bottom of the vial (see Figure 12).

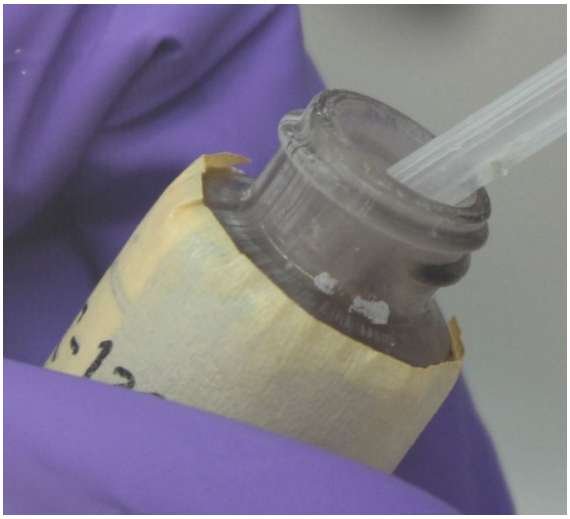


Figure 11. Empty C138 vial after transfer of Pu sulfate.

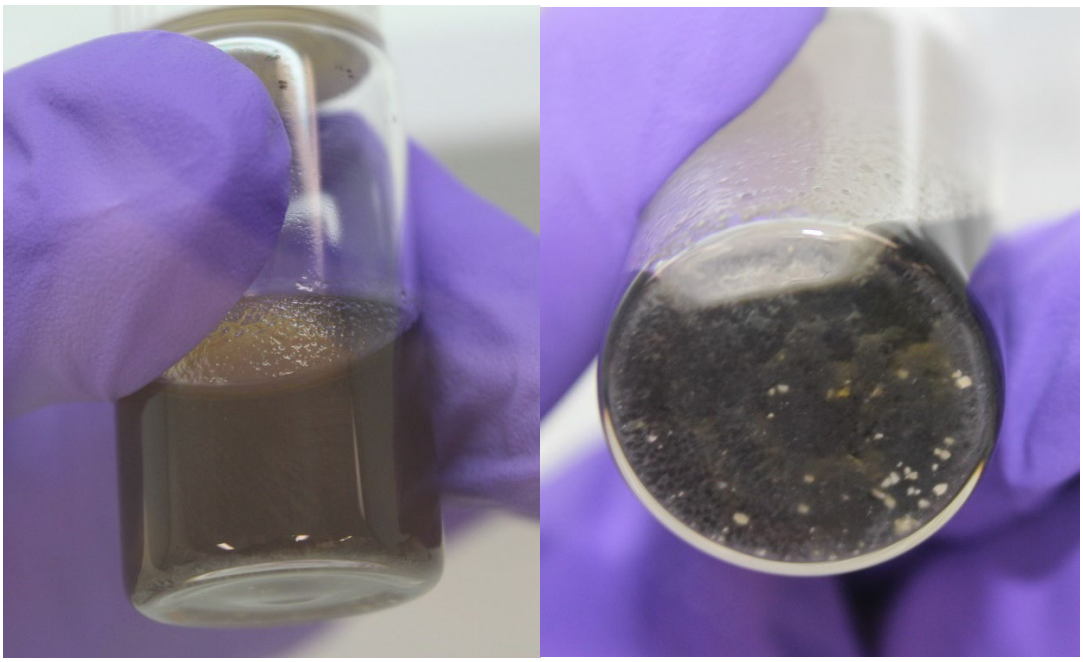


Figure 12. New glass vial with dissolved Pu sulfate and persistent white solid from the original vial.

Purification and preparation of primary solution

Anion Exchange

Pu purification via anion exchange proceeded according to the revised project plan. The dissolved Pu sulfate in 8 M HNO3/0.00105 M HF was loaded directly onto the preconditioned anion exchange column and formed a forest green Pu nitrate band that occupied ~40% of the column volume. Initially a faint pink band travelled below the green band (Figure 13, far left) and eluted in the first 20 mL of 8 M HNO_3. For C137A this was collected separately from the rest of the 8M HNO_3 fraction as it was not yet known how much of the neutral sulfate complex would prevail and be lost in the column wash. Later measurements determined that 235.10 ± 0.02 mg Pu was recovered in the purified solution, corresponding to 98.44% yield assuming the unit started as 250 mg on the Oct 1971 reference date. This demonstrated that the large excess of nitric acid was effective at overwhelming the sulfate complex to form the anionic nitrate complex and the pink color was likely due to the relatively large amount of Am in the material. All anion exchange columns proceeded without incident according to the revised work plan. Column flow proceeded by gravity and each anion exchange column took between 7 and 8 hours to complete including preconditioning. Figure 13 shows representative photos of the column at different steps in the process. Figure 14 shows the evaporation of HCl/HI through the impinger system for conversion to nitrate before and after Column 2.

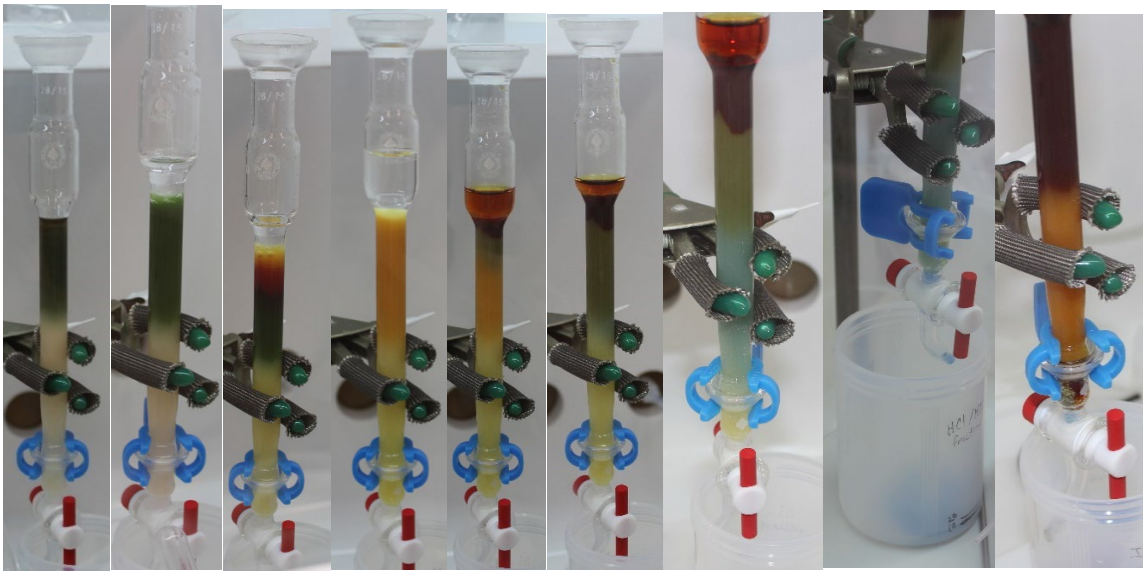


Figure 13. Anion exchange column at different phases of the process, chronologically from left to right from loading Pu in 8 M HNO_3 to washing the column with 8 M HNO_3 then 10 M HCl to Pu elution in 10:1 10 M HCl/HI.

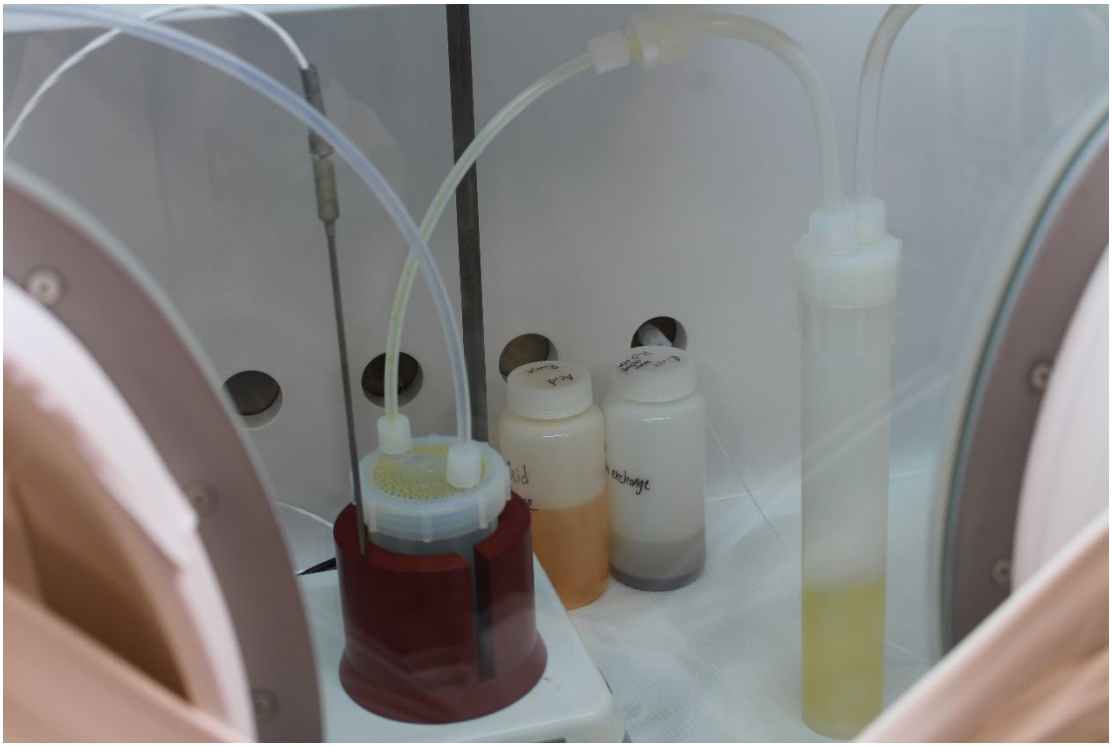


Figure 14. Evaporation of HCl/HI solution through Teflon impingers for conversion of eluted Pu to nitrate form in nitric acid.

Hold points 1 and 2 gamma spectrometry results

Gamma spectrometry was used as described in the project plan to assess the yield and efficiency of the purification. The Pu solutions in the 240 mL Savillex jars were counted 20 cm above an up-looking Canberra broad-energy Ge detector (BEGe, 31 mm x 69 mm diameter) with a 0.076-inch-thick Al absorber under the jar. Data were collected using a Canberra Lynx digitizer with trapezoidal peak shaping settings of 8.8 µsec rise time and 1.2 µsec flat top. To estimate the efficiency, curve a reference efficiency curve was measured by placing a certified ^{152}Eu and ^{133}Ba point sources (Eckert & Ziegler) inside a clean Savillex jar with the Al absorber and the 20 cm spacer. Starting with the reference curve, Ortec ANGLE was used to model the geometry-corrected efficiency curve for the jar with solution. After the Hold point 3 measurements were made on C137A by isotope dilution mass spectrometry (IDMS, with a Nu Instruments inductively coupled plasma mass spectrometer) the calculated total mg Pu at hold-point 3 and the gamma spectrum from hold point 2 were used to determine the empirical efficiency for key ^{239}Pu peaks. Which agreed, within uncertainty, with the modelled efficiencies and were used for the Pu estimates only going forward. The mg total Pu was estimated using the 129.3 keV gamma peak for ^{239}Pu quantification and the ^{241}Am activity was estimated from the 59.5 keV peak. Results for Hold points 2 and 3 are summarized in Table 3. Uncertainty for these estimates is dominated by absolute efficiency error and estimated at approximately 3% for the Pu and 10% for the Am.

Table 3. Results of gamma spectrometry estimates for hold points 1 and 2.

CRM Material	Hold Point 1 mg Pu	Hold Point 2 mg Pu	Hold Point 2 Bq ^{241}Am
C137A	234	235	4.66E4
C136A	237	233	3.39E4
C138A	249	247	6.36E3

Preparation of primary solutions and hold point 3 ICP-MS results

The primary solutions were prepared according to the project plan. Results of IDMS measurements for hold point 3 are given in Table 4. To convert the measured mg Pu per g solution to mg/mL, the solution was assumed to be 1.13 g/mL. Uncertainties in Table 4 do not include density uncertainty.

Table 4. Results of IDMS measurements for hold point 3.

CRM Material	C137A	C136A	C138A
239Pu mg/g solution	0.4592(8)	0.4987(6)	0.5615(9)
Total Pu mg/g solution	0.5812(9)	0.5776(7)	0.611(1)
mg Pu/ mL	0.668(1)	0.6527(8)	0.690(1)
Total mg Pu	235.10(2)	234.3	247.7(5)
Estimated yield %	98.4	98.1	99.9
mL dispensed per unit	1.58	1.60	1.53

Preparation of CRM units

Dispensing of units

Units of each CRM were dispensed into clean 30 mL FEP bottles using a Hamilton 600 dispenser according to the project plan. Figures 15 and 16 show representative photos of the primary solution being dispensed, and the dispensing station, respectively. Table 5 summarizes notes from each dispensing session, and weighing details are given in Appendix B.

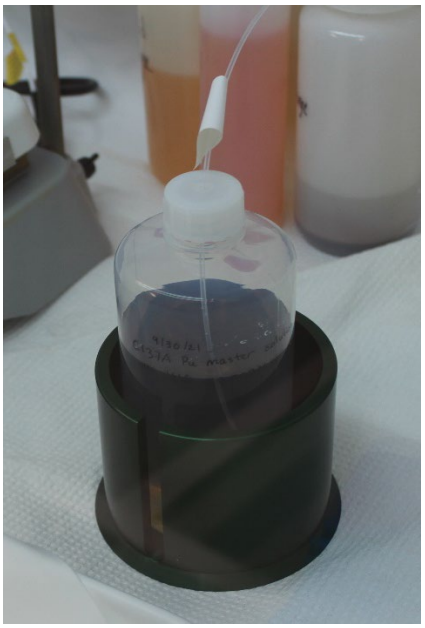


Figure 15. C137A primary solution being dispensed.

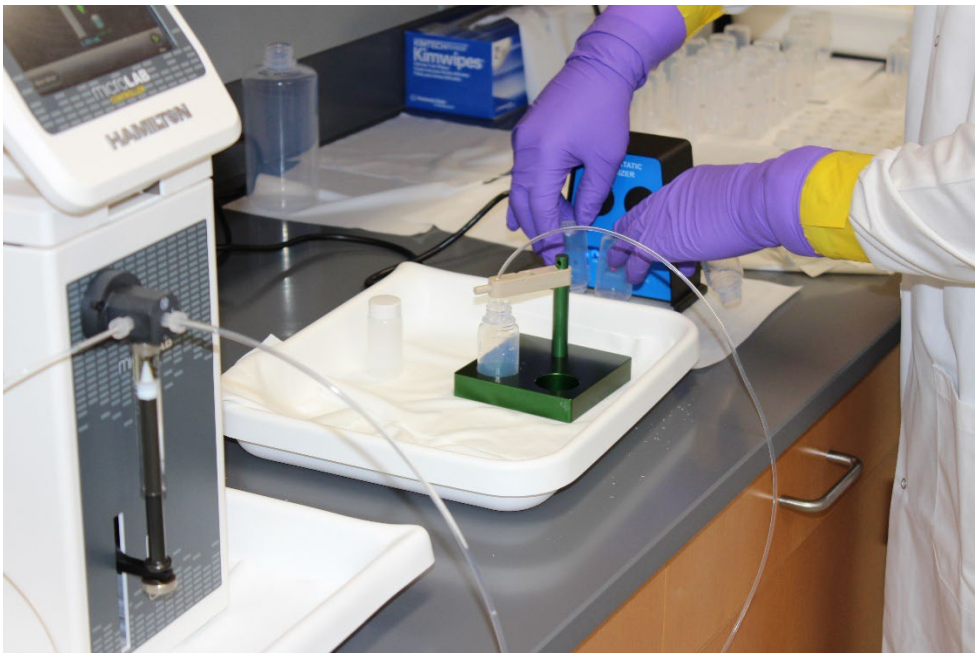


Figure 16.CRM unit dispensing station on the benchtop.

Table 5. Notes about dispensing of CRM units.

CRM Material	C137A	C136A	C138A
Mass of unit 1 (g)	1.806	N/A	1.668
Number of units dispensed	132	130	130
Notes	Units 18 and 66 had small bubbles dispensed.	Mass of unit 1 not recorded	Units 35, 63, 81, 88, and 119 had small bubbles dispensed.

Analytical aliquots

Analytical aliquots X, Y and Z were dispensed intermittently with the CRM units for IDMS measurements of Pu, U, Np, and Am as described in the project plan. Results from C137A and C136A [2] and for C138A [3] are described in separate reports.

Evaporation of units

Units were evaporated in batches of 15-20 units at 85° C in an Analab® heat block and hot plate as described in the project plan. Most units were heated for between 17 and 24 hours for full evaporation, details on heating times are given in Appendix C. No contamination was detected on smear surveys of the heating block in between batches. Figure 17 shows a batch of units

evaporating on the heating block. There was some variability observed in the appearance of the plutonium residue in the units; representative examples are shown in Figure 18.

Figure 17. 15 CRM137A units gently evaporating on an Analab® hot plate with heating block, set to 85° C.

Figure 18. Representative examples of C137A Pu residues in FEP bottles. While most units evaporated to condensed green-black dots (left), others appeared like a brown porous layer (right).

Packaging of units

Units were labelled and packaged according to the project plan. Figures 19-24 show representative units of each CRM with each layer of packaging.

Figure 19. Unit 1 of C137A with label applied to bottle (left), inside labeled zip-lock mylar pouch (middle), and pouch placed inside cardboard mailer tube (right).

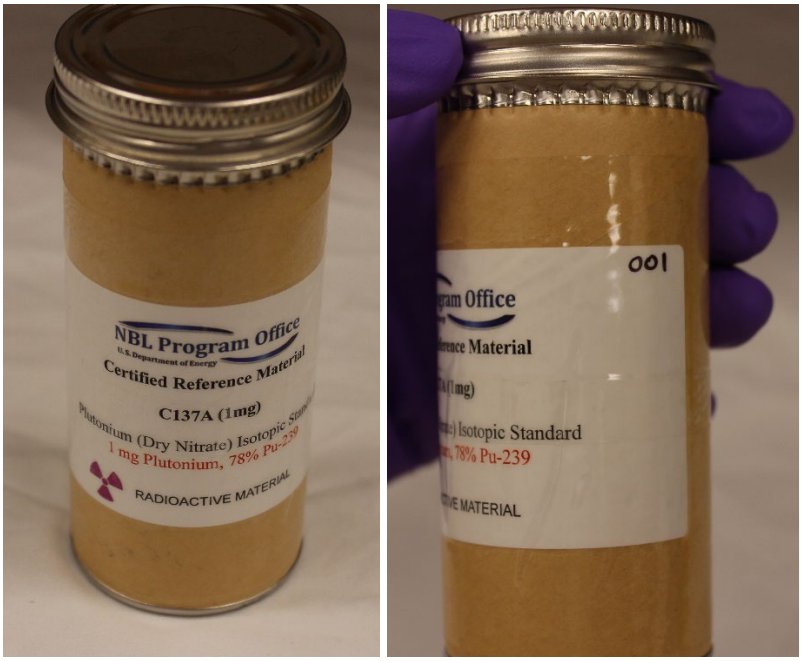


Figure 20. Unit 1 of C137A packaged inside the labelled cardboard mailer tube.

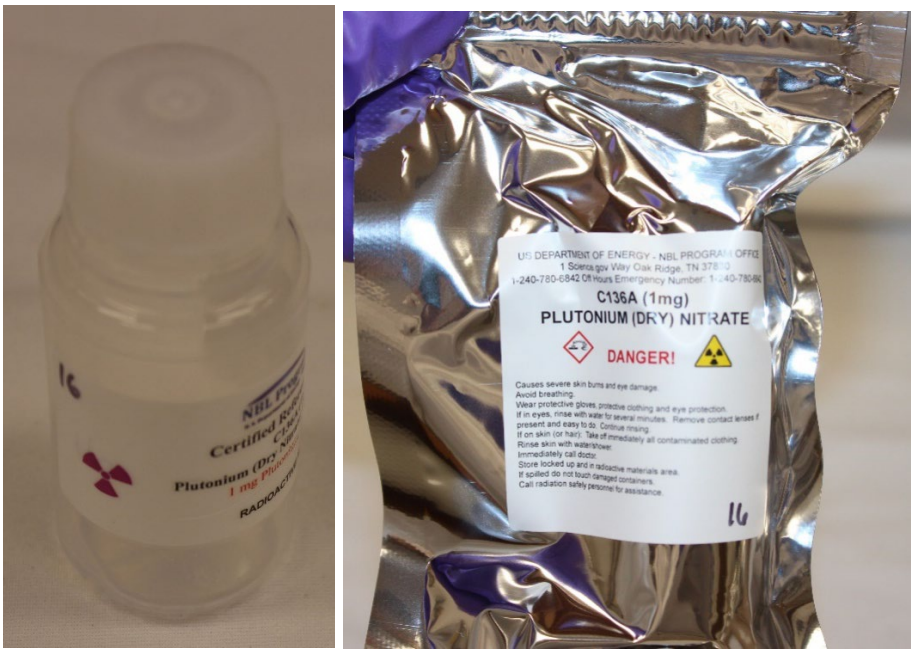


Figure 21. Unit 16 of C136A with label applied to bottle (left), and inside labeled zip-lock mylar pouch (right).

Figure 22. Unit 16 of C136A packaged in cardboard mailer tube.

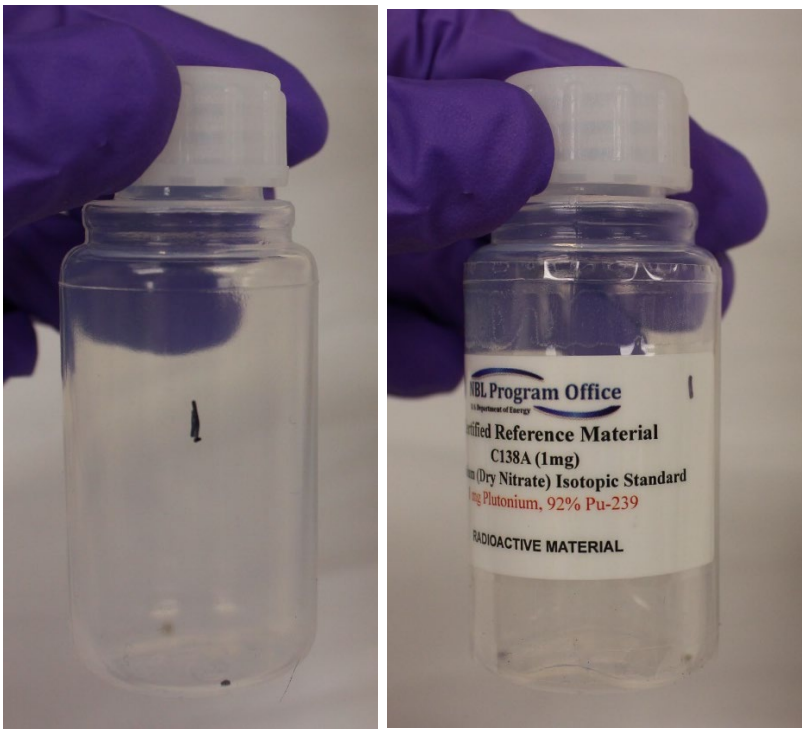


Figure 23. Unit 1 of C138A before(left) and after(right) applying NBL PO label to the FEP bottle.

Figure 24. Unit 1 of C138A packaged in Mylar zip-lock pouch (left) and in cardboard mailer tube (right).

Shipping of CRM units

Shipping of analytical units

Select units of each CRM were distributed to Los Alamos National Laboratory (LANL), Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL) and Idaho National Laboratory (INL) for the isotopic measurement campaign as directed by NBL PO. The same unit numbers were selected for all three CRMs. Table 6 summarizes these shipments.

Laboratory	*LANL*	*PNNL*	*ORNL*	*INL*
Technical POC	Kattathu J Mathew, kmathew@lanl.gov (505)667-6016	Connor Hilton, Connor.Hilton@pnnl.gov 509-372-6512	Cole R. Hexel, Hexelcr@ORNL.gov 865.574.2449	Luiza Gimenes Rodrigues Albuquerque, luiza.albuquerque@inl.gov 208-284-1533
Unit numbers shipped	15, 71, 103	20, 85, 127	4, 52, 113	45, 90
Ship date C137A	12/8/2021	12/8/2021	3/2/2022	12/20/2021
Ship date C136A	3/21/2023	3/7/2023	3/8/2023	3/7/2023
Ship date C138A	6/24/2024	7/2/2024	7/22/2024	6/24/2024

Shipping of remaining units to NBL PO distribution center

The remaining units of each CRM were packaged into 30-gallon drums and shipped to Mickey Finch and Curtis Hawk at Y-12 facility on November 19, 2024. In separate attachments shipping documents are provided for C137A (121 units, TID 003777 / PRL 7000005043), C136A (119 units, TID 003776 / PRL 7000005043) and C138A (119 units, TID 003778 / PRL 7000005126). Figures 25-27 show the inside package of C137A, C136A, and C138A with their container ID labels. An empty fiberboard box was used as spacer for each drum to help prevent any movement during the shipping process (Figure 28). Figure 29 shows the three 30-gallon drums, and Figures 30-32 show the container ID label applied to the outside of each drum and the LLNL Materials Management Vault and Transportation Group (MM V&TG) cable seal that it was shipped with.

Figure 25. Packaged C137A units inside the drum.

Figure 26. Packaged C136A units inside the drum.

Figure 27. Packaged C138A units inside the drum.

Figure 28. Example drum with empty spacer box on top of packaged units to reduce movement during shipping.

Figure 29. Three 30 gallon drums containing packaged CRMs for shipment.

Figure 30. C137A container label and MM V&TG cable seal.

Figure 31.C136A container label and MM V&TG cable seal.

Figure 32. C138A container label and MM V&TG cable seal.

Residual purified plutonium

After units were dispensed, the remaining purified plutonium solution was transferred back to a 240 mL Savillex jar and evaporated to leave a glassy nitrate residue. A representative photo is shown in Figure 33. Each jar was packaged and transferred to the custody of Kiel Holliday in B332, where they are being stored for the NBL PO, and are logged into LLNL's inventory system as "C137 residue", "C136 residual Pu", and "C138A residue", respectively. Figures 34-37 show photos of the packaged residues.

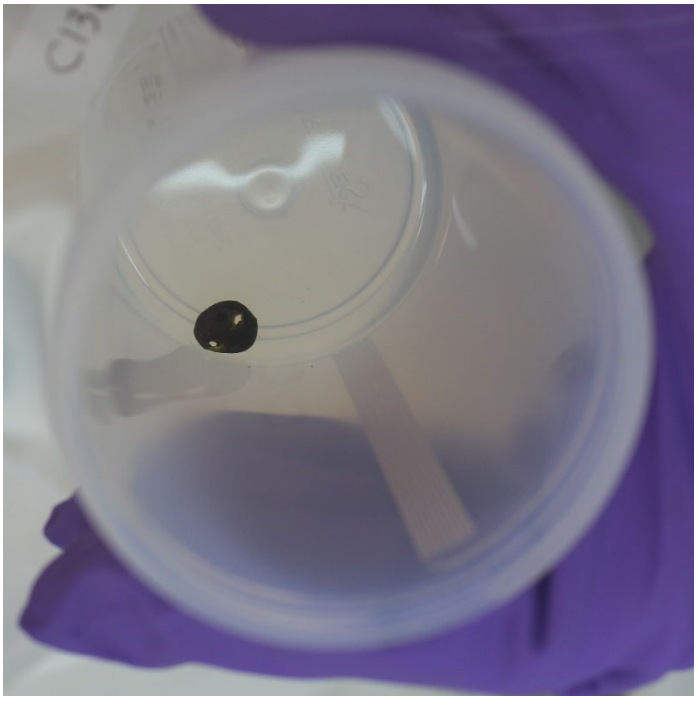


Figure 33. C136A residual Pu after evaporation.

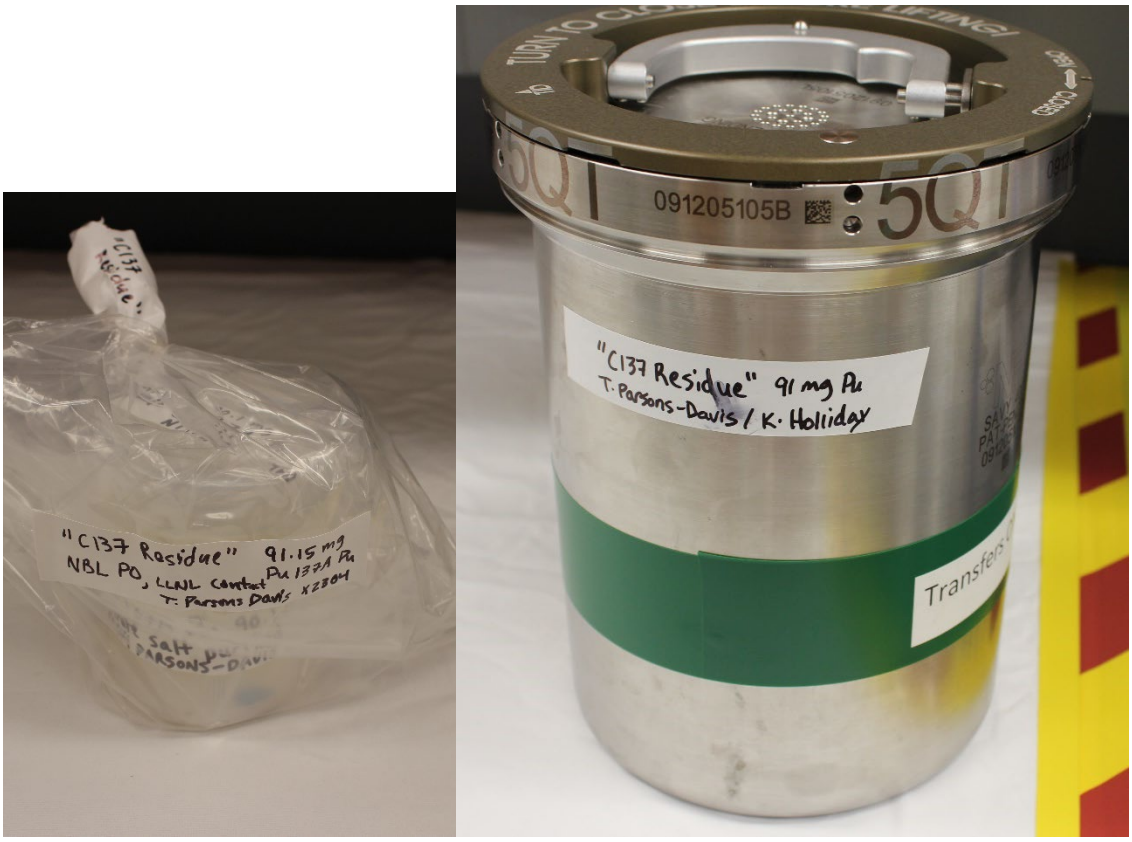


Figure 34. Residual C137A plutonium called "C137 Residue"(left) and SAVY container used for transport and storage (right).

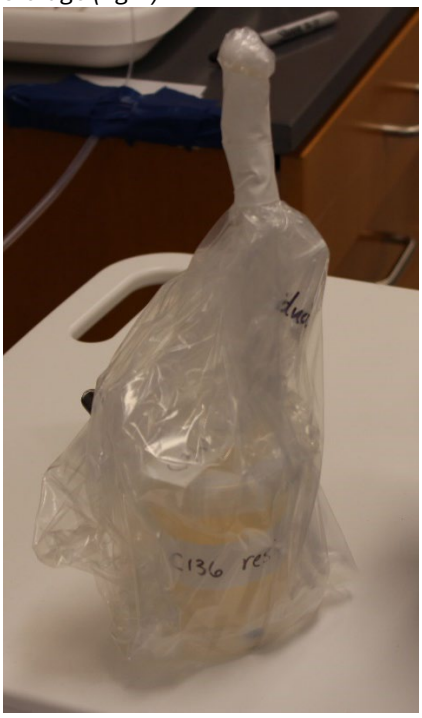


Figure 35. Residual C136A plutonium called "C136 residual Pu".

Figure 36. C138A plutonium residue, called "C138A residue".

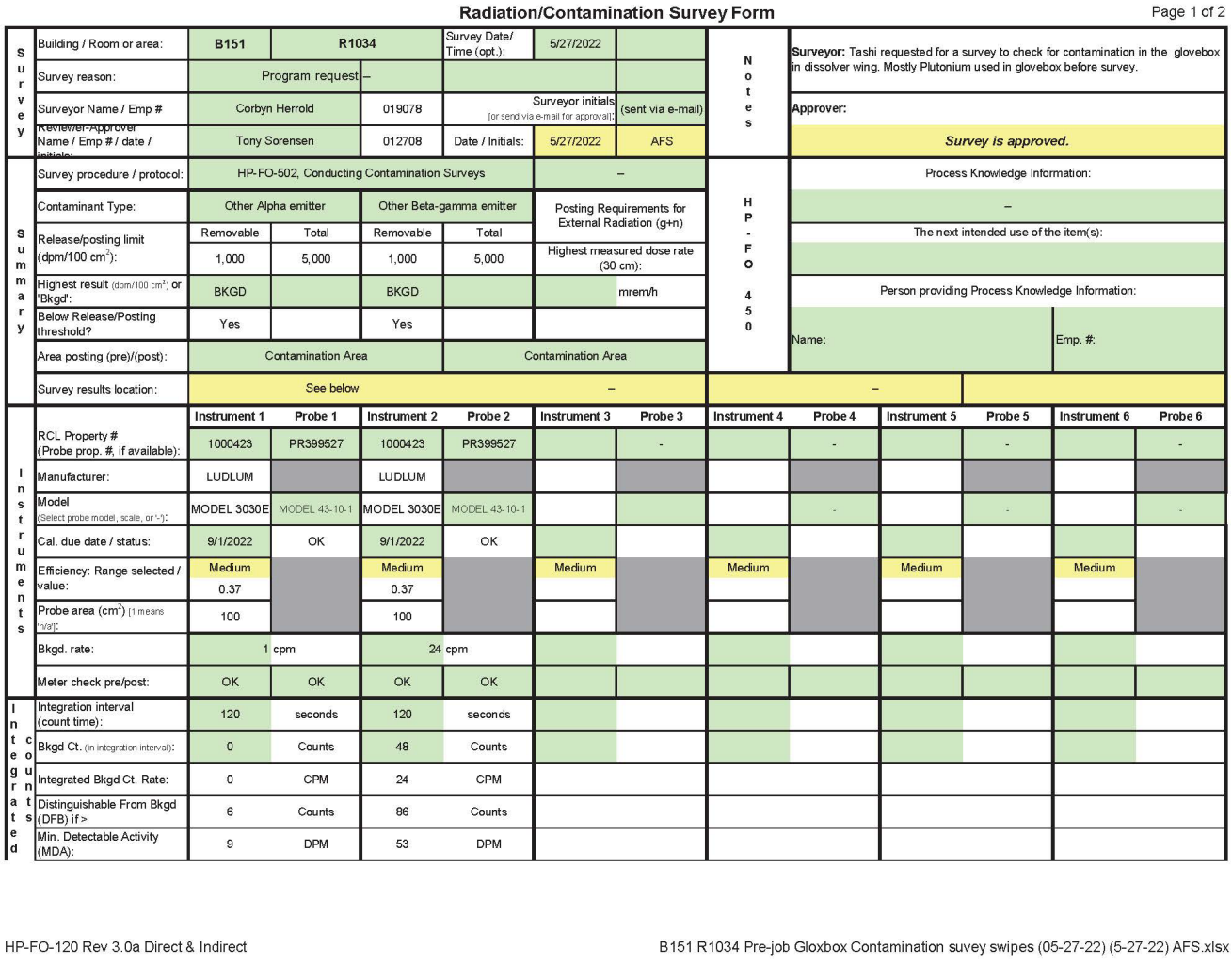
References

1. T. Parsons-Davis, R. Henderson, R. Williams, "*Revised Project Plan for Purification and Production of Plutonium Isotopic Reference Materials C136A, C137A and C138A"* LLNL-MI-823675 (May 2022).
2. R. Williams, J. Wimpenny, and T. Parsons-Davis, "*New NBL Pu Isotopic Standards C137A and C136A as Working Reference Materials for Radiochronometry in Nuclear Forensics*" LLNL-TR-846072 (March 2023).
3. J. Wimpenny, C. Tarng, and T. Parsons-Davis, "*Determination of Trace Actinide Abundances in the CRM 138-A Plutonium Standard"* LLNL-TR-2010357 (June 19, 2025).

Appendix A: Contamination surveys

Pre-production glovebox smear surveys

Prior to production of CRM 136A and CRM 138A production, an LLNL radiation safety technician wiped multiple 100 cm2 spots inside the glovebox and counted them via liquid scintillation to verify the box was free from contamination from the previous CRM production activities. This was not needed for C137A as it was the first radioactive material to enter the glovebox. No contamination was detected in the glovebox prior to C136A production in the survey performed 5/27/2022. Figures A1 and A2 show pages 1 and 2 of the survey form. Table A1 describes the 9 smears that were performed on 11/2/2023 as a prerequisite to C138A production. The results (Figure A4) revealed that the inside of the 240 mL jar heating block and the hot plate had removable alpha contamination. They were decontaminated and covered with foil, then re-surveyed on 11/3/2023 and came back clean. Figures A3 and A4 show the survey results from the 11/2/2023 survey and Figures A5 and A6 show the results from the 11/3/2023 surveys. Although the format of the survey reports shared by LLNL's ES&H team varied, the survey procedure and instrument are standard, and the significance of the results are consistent. Surveys are also provided as separate pdf attachments.



Radiation/Contamination Survey Form

Page 1 of 2

Survey	Building / Room or area:	B151	R1034			Survey Date/ Time (opt.):	5/27/2022		Notes	**Surveyor:** Tashi requested for a survey to check for contamination in the glovebox in dissolver wing. Mostly Plutonium used in glovebox before survey.							
	Survey reason:	Program request –															
	Surveyor Name / Emp #	Corbyn Herrold		019078		Surveyor initials [or send via e-mail for approval]:		(sent via e-mail)		**Approver:**							
	Reviewer-Approver Name / Emp # / date / initials:	Tony Sorensen		012708		Date / Initials:	5/27/2022	AFS		***Survey is approved.***							
Summary	Survey procedure / protocol:	HP-FO-502, Conducting Contamination Surveys				–			HP-FO-450	Process Knowledge Information:							
	Contaminant Type:	Other Alpha emitter		Other Beta-gamma emitter		Posting Requirements for External Radiation (g+n)				–							
	Release/posting limit (dpm/100 cm²):	Removable	Total	Removable	Total					The next intended use of the item(s):							
		1,000	5,000	1,000	5,000	Highest measured dose rate (30 cm):											
	Highest result (dpm/100 cm²) or 'Bkgd':	BKGD		BKGD			mrem/h			Person providing Process Knowledge Information:							
	Below Release/Posting threshold?	Yes		Yes						Name:		Emp. #:					
	Area posting (pre)/(post):	Contamination Area		Contamination Area													
	Survey results location:	See below		–						–							
Instruments		**Instrument 1**	**Probe 1**	**Instrument 2**	**Probe 2**	**Instrument 3**	**Probe 3**			**Instrument 4**	**Probe 4**	**Instrument 5**	**Probe 5**	**Instrument 6**	**Probe 6**		
	RCL Property # (Probe prop. #, if available):	1000423	PR399527	1000423	PR399527		-				-		-		-		
	Manufacturer:	LUDLUM		LUDLUM													
	Model (Select probe model, scale, or '-'):	MODEL 3030E	MODEL 43-10-1	MODEL 3030E	MODEL 43-10-1						-		-		-		
	Cal. due date / status:	9/1/2022	OK	9/1/2022	OK												
	Efficiency: Range selected / value:	Medium		Medium		Medium				Medium		Medium		Medium			
		0.37		0.37													
	Probe area (cm²) [1 means n/a]:	100		100													
	Bkgd. rate:	1 cpm		24 cpm													
	Meter check pre/post:	OK	OK	OK	OK												
Integrated counts	Integration interval (count time):	120	seconds	120	seconds												
	Bkgd Ct. (in integration interval):	0	Counts	48	Counts												
	Integrated Bkgd Ct. Rate:	0	CPM	24	CPM												
	Distinguishable From Bkgd (DFB) if >	6	Counts	86	Counts												
	Min. Detectable Activity (MDA):	9	DPM	53	DPM												

HP-FO-120 Rev 3.0a Direct & Indirect

B151 R1034 Pre-job Gloxbox Contamination suvey swipes (05-27-22) (5-27-22) AFS.xlsx

Figure A 1. Page one of glovebox smear survey report from 5/27/22 prior to C136A production.

Radiation/Contamination Survey Form

Survey	Building / Room or area:	B151	R1034		Survey Date/ Time (opt.):	5/27/2022		Notes	Surveyor: Tashi requested for a survey to check for contamination in the glovebox in dissolver wing. Mostly Plutonium used in glovebox before survey.			
	Survey reason:	Program request –										
	Surveyor Name / Emp #	Corbyn Herrold		019078	[or send via e-mail for approval]:		(sent via e-mail)		Approver:			
	Reviewer-Approver Name / Emp # / date / initials:	Tony Sorensen		012708	Date / Initials:	5/27/2022	AFS		*Survey is approved.*			
Results	**Type of survey:**	Swipe Counter		Swipe Counter		-		-		-		-
	Location (see sketch or map or describe below)	Instrument 1 Results		Instrument 2 Results		-		-		-		-
		Counts	dpm/swipe	Counts	dpm/swipe	-	-	-	-	-	-	-
1	Hood Floor Left of Hot Plate	1	Bkgd	26	Bkgd							
2	Center of hood floor	0	Bkgd	26	Bkgd							
3	Hot plate surface	1	Bkgd	31	Bkgd							
4	Inner chamber door and handle	3	Bkgd	29	Bkgd							
5	Right of hood floor	1	Bkgd	34	Bkgd							

Figure A 2. Page one of glovebox smear survey report from 5/27/22 prior to C136A production.

Table A1. Description of numbered smear survey wipes taken 11/2/2023 prior to C138A production.

Smear survey wipe	Location or item
1	Antechamber
2	Shelf
3	Left floor
4	Middle floor
5	Right floor
6	Hot plate
7	Impingers
8	Door handle between antechamber and box
9	Heat block for evaporating 240 mL jars

Figure A 3. Page 1 of LSC results for smear survey taken in the glovebox on 11/2/2023 prior to C138A production.

11/2/2023 3:12:55 PM **QuantaSmart (TM) - 5.2 - Serial# SGLO50191222** **Page 1**

Protocol# 1 - GAB_H3_2min.lsa **User: Default**

GAB_H3_2min

Assay Definition

Assay Description:

Assay Type: Alpha/Beta
Report Name: GAB_H3_2min
Output Data Path: C:\Packard\Tricarb\Results\Default\GAB_H3_2min\20231102_1436
Raw Results Path: C:\Packard\Tricarb\Results\Default\GAB_H3_2min\20231102_1436\20231102_1436.results
Comma-Delimited File Name: C:\Packard\Tricarb\Results\Default\GAB_H3_2min\20231102_1436\Report1.csv
Assay File Name: C:\Packard\TriCarb\Assays\GAB_H3_2min.lsa

Count Conditions

Nuclide: GAB-H3
Quench Indicator: tSIE
External Std Terminator (sec): 0.5 2s%
Pre-Count Delay (min): 0.00
Alpha/Beta Standards:
Low Energy: AM/CL
Count Time (min): 2.00
Count Mode: Normal
Assay Count Cycles: 1 Repeat Sample Count: 1
Number of Vials/Sample: 1 Calculate % Reference: Off Count Alpha/Beta Standards: No

Background Subtract

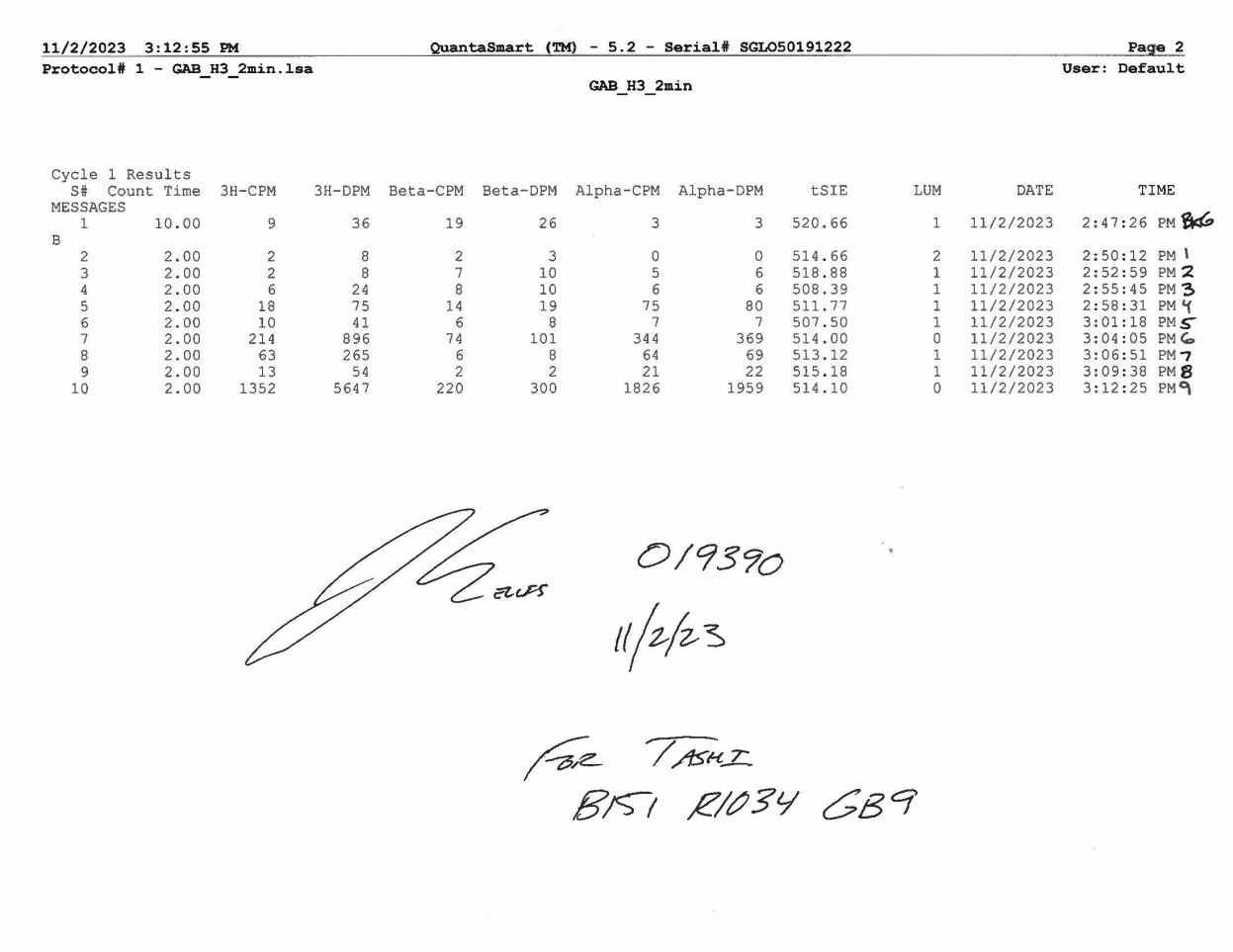
Background Subtract: On - 1st Vial
Low CPM Threshold: Off
2 Sigma % Terminator: Off

In Use Discriminator: 145

Regions	LL	UL	Bkg Subtract
Beta A	0.0	18.6	1st Vial
Beta B	18.6	2000.0	1st Vial
Alpha	18.6	1000.0	1st Vial

Count Corrections

Static Controller: On Luminescence Correction: Off GCT: n/a
Colored Samples: n/a Heterogeneity Monitor: n/a PAC: Disabled
Coincidence Time (nsec): 18 Delay Before Burst (nsec): 75 PAC Strength: n/a Auxiliary Spectrum: n/a



11/2/2023 3:12:55 PM QuantaSmart (TM) - 5.2 - Serial# SGLO50191222 Page 2

Protocol# 1 - GAB_H3_2min.lsa User: Default

GAB_H3_2min

Cycle 1 Results

S#	Count Time	3H-CPM	3H-DPM	Beta-CPM	Beta-DPM	Alpha-CPM	Alpha-DPM	tSIE	LUM	DATE	TIME	MESSAGES
1	10.00	9	36	19	26	3	3	520.66	1	11/2/2023	2:47:26 PM	BKG B
2	2.00	2	8	2	3	0	0	514.66	2	11/2/2023	2:50:12 PM	1
3	2.00	2	8	7	10	5	6	518.88	1	11/2/2023	2:52:59 PM	2
4	2.00	6	24	8	10	6	6	508.39	1	11/2/2023	2:55:45 PM	3
5	2.00	18	75	14	19	75	80	511.77	1	11/2/2023	2:58:31 PM	4
6	2.00	10	41	6	8	7	7	507.50	1	11/2/2023	3:01:18 PM	5
7	2.00	214	896	74	101	344	369	514.00	0	11/2/2023	3:04:05 PM	6
8	2.00	63	265	6	8	64	69	513.12	1	11/2/2023	3:06:51 PM	7
9	2.00	13	54	2	2	21	22	515.18	1	11/2/2023	3:09:38 PM	8
10	2.00	1352	5647	220	300	1826	1959	514.10	0	11/2/2023	3:12:25 PM	9

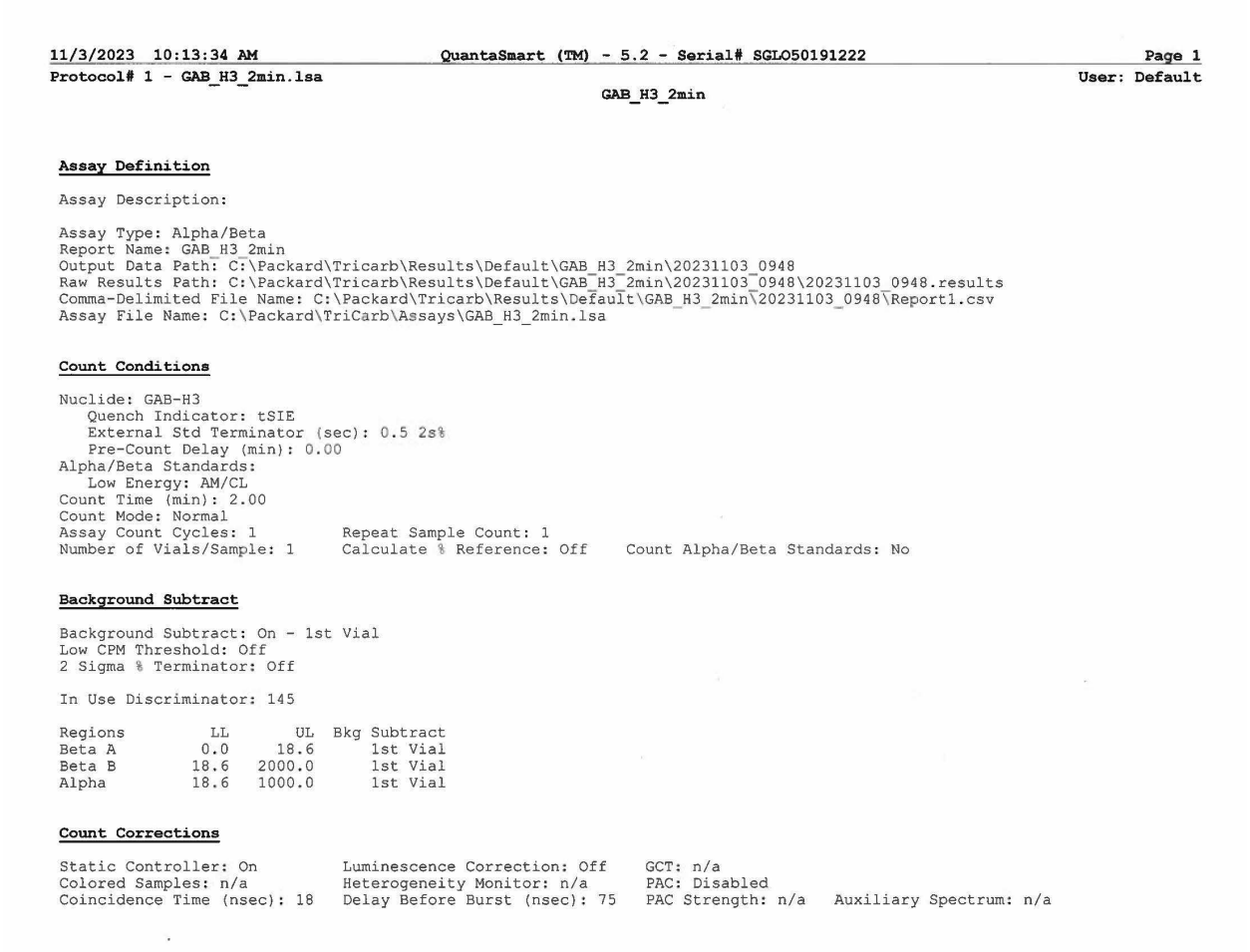
019390

11/2/23

FOR TASHI

B151 R1034 GB9

Figure A 4. Page 2 of LSC results for smear survey taken in the glovebox on 11/2/2023 prior to C138A production.



11/3/2023 10:13:34 AM QuantaSmart (TM) - 5.2 - Serial# SGLO50191222 Page 1
Protocol# 1 - GAB_H3_2min.lsa User: Default
GAB_H3_2min

Assay Definition

Assay Description:

Assay Type: Alpha/Beta
Report Name: GAB_H3_2min
Output Data Path: C:\Packard\Tricarb\Results\Default\GAB_H3_2min\20231103_0948
Raw Results Path: C:\Packard\Tricarb\Results\Default\GAB_H3_2min\20231103_0948\20231103_0948.results
Comma-Delimited File Name: C:\Packard\Tricarb\Results\Default\GAB_H3_2min\20231103_0948\Report1.csv
Assay File Name: C:\Packard\TriCarb\Assays\GAB_H3_2min.lsa

Count Conditions

Nuclide: GAB-H3
Quench Indicator: tSIE
External Std Terminator (sec): 0.5 2s%
Pre-Count Delay (min): 0.00
Alpha/Beta Standards:
Low Energy: AM/CL
Count Time (min): 2.00
Count Mode: Normal
Assay Count Cycles: 1 Repeat Sample Count: 1
Number of Vials/Sample: 1 Calculate % Reference: Off Count Alpha/Beta Standards: No

Background Subtract

Background Subtract: On - 1st Vial
Low CPM Threshold: Off
2 Sigma % Terminator: Off

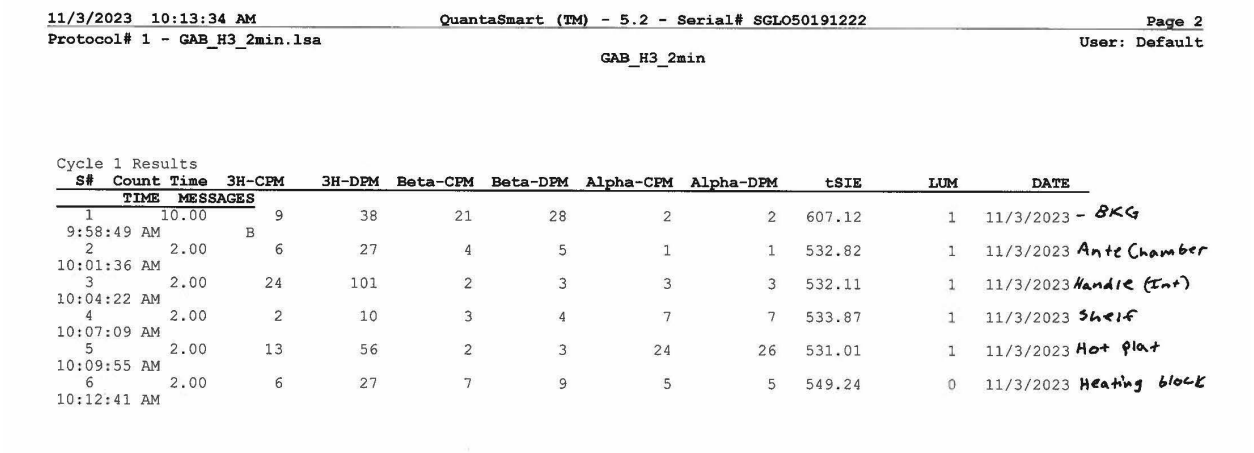
In Use Discriminator: 145

Regions	LL	UL	Bkg Subtract
Beta A	0.0	18.6	1st Vial
Beta B	18.6	2000.0	1st Vial
Alpha	18.6	1000.0	1st Vial

Count Corrections

Static Controller: On Luminescence Correction: Off GCT: n/a
Colored Samples: n/a Heterogeneity Monitor: n/a PAC: Disabled
Coincidence Time (nsec): 18 Delay Before Burst (nsec): 75 PAC Strength: n/a Auxiliary Spectrum: n/a

Figure A 5. Page 1 of smear survey wipes taken 11/3/2023 prior to C138A production.



11/3/2023 10:13:34 AM QuantaSmart (TM) - 5.2 - Serial# SGLO50191222 Page 2
Protocol# 1 - GAB_H3_2min.lsa User: Default
GAB_H3_2min

Cycle 1 Results

S#	Count Time	3H-CPM	3H-DPM	Beta-CPM	Beta-DPM	Alpha-CPM	Alpha-DPM	tSIE	LUM	DATE	
TIME	MESSAGES										
1	10.00	9	38	21	28	2	2	607.12	1	11/3/2023	- BKG
9:58:49 AM	B										
2	2.00	6	27	4	5	1	1	532.82	1	11/3/2023	Ante Chamber
10:01:36 AM											
3	2.00	24	101	2	3	3	3	532.11	1	11/3/2023	Handle (Ent)
10:04:22 AM											
4	2.00	2	10	3	4	7	7	533.87	1	11/3/2023	Shelf
10:07:09 AM											
5	2.00	13	56	2	3	24	26	531.01	1	11/3/2023	Hot plat
10:09:55 AM											
6	2.00	6	27	7	9	5	5	549.24	0	11/3/2023	Heating block
10:12:41 AM											

Figure A 6. Page 2 of LSC results for smear survey taken in the glovebox 11/3/2023 prior to C138A production.

Heating block smear surveys during evaporation of units

As described in the project plan, LLNL radiation safety technicians completed smear surveys of the Analab heating block used to evaporate solution from the 30 mL FEP unit bottles in between the first few batches for each CRM. All the surveys showed that there was no contamination of the

heating block. Smear surveys taken of the heating block after evaporation of the first four batches of C137A units were taken on 10/13/2021, 10/14/2021, 10/18/2021 and 10/20/2021. Smear surveys taken of the heating block after evaporation of the first three batches of C136A units were taken on 7/19/2022, 7/21/2022, and 7/25/2022. Smear surveys taken of the heating block after evaporation of the first three batches of C138A units were taken on 1/05/2024, 1/12/2024, and 7/25/2022. All smear survey results from the heating block are provided as separate pdf attachments.

Surveys for material transfers and shipping

LLNL policy requires that the outer packaging of all radiological materials to be shipped or transferred to a different building be surveyed by a radiation safety technician and released as free from contamination. This process was completed for shipment of all analytical units (3 each to LANL, PNNL, ORNL, and INL), transfer of materials between B151 and B332 at LLNL, and shipment of the three drums to Y12. No contamination was detected in any material transfer surveys associated with this project. Survey results are provided with the shipping document for the final delivery of units to Y12.

Appendix B: weights and balance checks

Weights for hold-point 3 IDMS measurements

Hold point 3 Pu IDMS measurements required sample and spike weighing and associated calibrated weight checks. These are recorded on separate tabs of Excel workbooks containing the results, which are provided as separate attachments.

Weights as a check for unit volume dispensing

The first unit of each CRM was to be weighed as a check that the volume dispensed by the Hamilton Controller was as expected. Unfortunately, no weight was recorded associated with C136A. Check weight and sample weights associated with dispensing C137A and C138A are given in Tables B1.

Table B1. Weights recorded from Mettler Toledo XPR204 balance in B151 R1034 with calibrated check weight set Mettler Toledo B53844245 and first dispensed units of CRMs.

CRM	137A	138A
Date	10/11/2021	1/4/2023
1 g check	1.0000	1.0001
2 g check	2.0000	2.0001
5 g check	5.0002	5.0002
10 g check	10.0004	10.0001
20 g check	20.0003	N/A
50 g check	50.0006	49.9990
Empty unit 1 bottle (g)	20.4305	19.2318
Bottle with solution (g)	22.2365	20.9006
solution(g)	1.8060	1.6688

Appendix C: unit evaporation times

The heating start and end times, and total number of hours each individual unit was held at 85˚C are given in Tables C1-C3 for C137A, C136A and C138A.

Table C1. The evaporation start and end times, and total number of hours held at 85˚C for each individual C137A unit.

UNIT	EVAPORATION START	EVAPORATION END	TOTAL TIME (HOURS)
1	10/11/21 15:50	10/12/21 8:30	16.67
2	10/11/21 15:50	10/12/21 12:50	21.00
3	10/11/21 15:50	10/12/21 8:30	16.67
4	10/11/21 15:50	10/12/21 8:30	16.67
5	10/11/21 15:50	10/12/21 8:30	16.67
6	10/11/21 15:50	10/12/21 8:30	16.67
7	10/11/21 15:50	10/12/21 8:30	16.67
8	10/11/21 15:50	10/12/21 8:30	16.67
9	10/11/21 15:50	10/12/21 12:50	21.00
10	10/11/21 15:50	10/12/21 12:50	21.00
11	10/11/21 15:50	10/12/21 12:50	21.00
12	10/11/21 15:50	10/12/21 8:30	16.67
13	10/11/21 15:50	10/12/21 16:45	24.92
14	10/11/21 15:50	10/12/21 12:50	21.00
15	10/11/21 15:50	10/12/21 12:50	21.00
16	10/13/21 12:15	10/14/21 10:55	22.67
17	10/13/21 12:15	10/14/21 10:55	22.67
18	10/13/21 12:15	10/14/21 10:55	22.67
19	10/13/21 12:15	10/14/21 10:55	22.67
20	10/13/21 12:15	10/14/21 15:25	27.17
21	10/13/21 12:15	10/14/21 10:55	22.67
22	10/13/21 12:15	10/14/21 10:55	22.67
23	10/13/21 12:15	10/14/21 10:55	22.67
24	10/13/21 12:15	10/14/21 10:55	22.67
25	10/13/21 12:15	10/14/21 10:55	22.67
26	10/13/21 12:15	10/14/21 10:55	22.67
27	10/13/21 12:15	10/14/21 10:55	22.67
28	10/13/21 12:15	10/14/21 10:55	22.67
29	10/13/21 12:15	10/14/21 13:05	24.83
30	10/13/21 12:15	10/14/21 10:55	22.67
31	10/14/21 16:55	10/15/21 9:15	16.33
32	10/14/21 16:55	10/15/21 9:15	16.33
33	10/14/21 16:55	10/15/21 9:15	16.33

34	10/14/21 16:55	10/15/21 9:15	16.33
35	10/14/21 16:55	10/15/21 13:00	20.08
36	10/14/21 16:55	10/15/21 9:15	16.33
37	10/14/21 16:55	10/15/21 9:15	16.33
38	10/14/21 16:55	10/15/21 16:00	23.08
39	10/14/21 16:55	10/15/21 17:15	24.33
40	10/14/21 16:55	10/15/21 9:15	16.33
41	10/14/21 16:55	10/15/21 9:15	16.33
42	10/14/21 16:55	10/15/21 9:15	16.33
43	10/14/21 16:55	10/15/21 16:00	23.08
44	10/14/21 16:55	10/15/21 9:15	16.33
45	10/18/21 10:40	10/19/21 9:00	22.33
46	10/18/21 10:40	10/19/21 9:00	22.33
47	10/18/21 10:40	10/19/21 9:00	22.33
48	10/18/21 10:40	10/19/21 9:00	22.33
49	10/18/21 10:40	10/19/21 9:00	22.33
50	10/18/21 10:40	10/19/21 9:30	22.83
51	10/18/21 10:40	10/19/21 9:00	22.33
52	10/18/21 10:40	10/19/21 9:00	22.33
53	10/18/21 10:40	10/19/21 10:20	23.67
54	10/18/21 10:40	10/19/21 9:00	22.33
55	10/18/21 10:40	10/19/21 9:00	22.33
56	10/18/21 10:40	10/19/21 9:00	22.33
57	10/18/21 10:40	10/19/21 9:00	22.33
58	10/18/21 10:40	10/19/21 9:00	22.33
59	10/18/21 10:40	10/19/21 9:00	22.33
60	10/19/21 9:30	10/20/21 8:45	23.25
61	10/19/21 9:30	10/20/21 8:45	23.25
62	10/19/21 9:30	10/20/21 8:45	23.25
63	10/19/21 9:30	10/20/21 8:45	23.25
64	10/19/21 9:30	10/20/21 8:45	23.25
65	10/19/21 9:30	10/20/21 8:45	23.25
66	10/19/21 9:30	10/20/21 8:45	23.25
67	10/19/21 9:30	10/20/21 14:15	28.75
68	10/19/21 9:30	10/20/21 8:45	23.25
69	10/19/21 9:30	10/20/21 8:45	23.25
70	10/19/21 9:30	10/20/21 8:45	23.25
71	10/19/21 9:30	10/20/21 8:45	23.25
72	10/19/21 9:30	10/20/21 8:45	23.25
73	10/19/21 9:30	10/20/21 8:45	23.25
74	10/19/21 9:30	10/20/21 8:45	23.25
75	10/19/21 9:30	10/20/21 8:45	23.25
76	10/19/21 9:30	10/20/21 8:45	23.25
77	10/19/21 9:30	10/20/21 8:45	23.25

78	10/19/21 9:30	10/20/21 8:45	23.25
79	10/19/21 10:20	10/20/21 8:45	22.42
80	10/20/21 19:15	10/21/21 12:35	17.33
81	10/20/21 19:15	10/21/21 12:35	17.33
82	10/20/21 19:15	10/21/21 9:30	14.25
83	10/20/21 19:15	10/21/21 9:30	14.25
84	10/20/21 19:15	10/22/21 9:20	38.08
85	10/20/21 19:15	10/21/21 18:50	23.58
86	10/20/21 19:15	10/21/21 18:50	23.58
87	10/20/21 19:15	10/21/21 18:50	23.58
88	10/20/21 19:15	10/21/21 18:50	23.58
89	10/20/21 19:15	10/21/21 18:50	23.58
90	10/20/21 19:15	10/22/21 9:20	38.08
91	10/20/21 19:15	10/21/21 18:50	23.58
92	10/20/21 19:15	10/21/21 18:50	23.58
93	10/20/21 19:15	10/22/21 9:20	38.08
94	10/20/21 19:15	10/21/21 18:50	23.58
95	10/20/21 19:15	10/21/21 18:50	23.58
96	10/20/21 19:15	10/21/21 18:50	23.58
97	10/20/21 19:15	10/21/21 18:50	23.58
98	10/20/21 19:15	10/22/21 9:20	38.08
99	10/20/21 19:15	10/21/21 18:50	23.58
100	10/21/21 9:30	10/22/21 10:45	25.25
101	10/21/21 9:30	10/22/21 9:20	23.83
102	10/21/21 12:35	10/22/21 9:20	20.75
103	10/21/21 12:35	10/22/21 9:20	20.75
104	10/21/21 18:50	10/23/21 20:00	49.17
105	10/21/21 18:50	10/22/21 15:25	20.58
106	10/21/21 18:50	10/22/21 15:25	20.58
107	10/21/21 18:50	10/22/21 15:25	20.58
108	10/21/21 18:50	10/22/21 15:25	20.58
109	10/21/21 18:50	10/22/21 10:45	15.92
110	10/21/21 18:50	10/22/21 20:00	25.17
111	10/21/21 18:50	10/22/21 15:25	20.58
112	10/21/21 18:50	10/23/21 20:00	49.17
113	10/21/21 18:50	10/22/21 15:25	20.58
114	10/21/21 18:50	10/22/21 20:00	25.17
115	10/21/21 18:50	10/22/21 15:25	20.58
116	10/22/21 9:20	10/23/21 20:00	34.67
117	10/22/21 9:20	10/23/21 20:00	34.67
118	10/22/21 9:20	10/23/21 20:00	34.67
119	10/22/21 9:20	10/23/21 20:00	34.67
120	10/22/21 9:20	10/23/21 20:00	34.67
121	10/22/21 9:20	10/23/21 20:00	34.67

122	10/22/21 9:20	10/23/21 20:00	34.67
123	10/22/21 15:25	10/23/21 20:00	28.58
124	10/22/21 10:45	10/23/21 20:00	33.25
125	10/22/21 10:45	10/23/21 20:00	33.25
126	10/22/21 15:25	10/23/21 20:00	28.58
127	10/22/21 15:25	10/23/21 20:00	28.58
128	10/22/21 15:25	10/23/21 20:00	28.58
129	10/22/21 15:25	10/23/21 20:00	28.58
130	10/22/21 15:25	10/23/21 20:00	28.58
131	10/22/21 15:25	10/23/21 20:00	28.58
132	10/22/21 20:00	10/23/21 20:00	24.00

Table C2. The evaporation start and end times, and total number of hours held at 85˚C for each individual C136A unit.

UNIT	EVAPORATION START	EVAPORATION END	TOTAL TIME (HOURS)
1	7/18/22 15:30	7/19/22 10:30	19.00
2	7/18/22 15:30	7/19/22 10:30	19.00
3	7/18/22 15:30	7/19/22 10:30	19.00
4	7/18/22 15:30	7/19/22 10:30	19.00
5	7/18/22 15:30	7/19/22 10:30	19.00
6	7/18/22 15:30	7/19/22 10:30	19.00
7	7/18/22 15:30	7/19/22 10:30	19.00
8	7/18/22 15:30	7/19/22 10:30	19.00
9	7/18/22 15:30	7/19/22 10:30	19.00
10	7/18/22 15:30	7/19/22 10:30	19.00
11	7/18/22 15:30	7/19/22 10:30	19.00
12	7/18/22 15:30	7/19/22 10:30	19.00
13	7/18/22 15:30	7/19/22 10:30	19.00
14	7/18/22 15:30	7/19/22 10:30	19.00
15	7/18/22 15:30	7/19/22 10:30	19.00
16	7/21/22 18:45	7/22/22 12:45	18.00
17	7/21/22 18:45	7/22/22 12:45	18.00
18	7/21/22 18:45	7/22/22 12:45	18.00
19	7/21/22 18:45	7/22/22 12:45	18.00
20	7/21/22 18:45	7/22/22 12:45	18.00
21	7/21/22 18:45	7/22/22 12:45	18.00
22	7/21/22 18:45	7/22/22 12:45	18.00
23	7/21/22 18:45	7/22/22 12:45	18.00
24	7/21/22 18:45	7/22/22 12:45	18.00
25	7/21/22 18:45	7/22/22 12:45	18.00
26	7/21/22 18:45	7/22/22 12:45	18.00
27	7/21/22 18:45	7/22/22 12:45	18.00

28	7/21/22 18:45	7/22/22 12:45	18.00
29	7/21/22 18:45	7/22/22 12:45	18.00
30	7/21/22 18:45	7/22/22 12:45	18.00
31	7/27/22 17:30	7/28/22 13:30	20.00
32	7/27/22 17:30	7/28/22 13:30	20.00
33	7/27/22 17:30	7/28/22 13:30	20.00
34	7/27/22 17:30	7/28/22 13:30	20.00
35	7/27/22 17:30	7/28/22 13:30	20.00
36	7/27/22 17:30	7/28/22 13:30	20.00
37	7/27/22 17:30	7/28/22 13:30	20.00
38	7/27/22 17:30	7/28/22 13:30	20.00
39	7/27/22 17:30	7/28/22 13:30	20.00
40	7/27/22 17:30	7/28/22 13:30	20.00
41	7/27/22 17:30	7/28/22 13:30	20.00
42	7/27/22 17:30	7/28/22 13:30	20.00
43	7/27/22 17:30	7/28/22 13:30	20.00
44	7/27/22 17:30	7/28/22 13:30	20.00
45	7/27/22 17:30	7/28/22 13:30	20.00
46	7/27/22 17:30	7/28/22 13:30	20.00
47	7/27/22 17:30	7/28/22 13:30	20.00
48	7/27/22 17:30	7/28/22 13:30	20.00
49	7/27/22 17:30	7/28/22 13:30	20.00
50	7/27/22 17:30	7/28/22 13:30	20.00
51	7/28/22 18:30	7/29/22 18:30	24.00
52	7/28/22 18:30	7/29/22 18:30	24.00
53	7/28/22 18:30	7/29/22 18:30	24.00
54	7/28/22 18:30	7/29/22 18:30	24.00
55	7/28/22 18:30	7/29/22 18:30	24.00
56	7/28/22 18:30	7/29/22 18:30	24.00
57	7/28/22 18:30	7/29/22 18:30	24.00
58	7/28/22 18:30	7/29/22 18:30	24.00
59	7/28/22 18:30	7/29/22 18:30	24.00
60	7/28/22 18:30	7/29/22 18:30	24.00
61	7/28/22 18:30	7/29/22 18:30	24.00
62	7/28/22 18:30	7/29/22 18:30	24.00
63	7/28/22 18:30	7/29/22 18:30	24.00
64	7/28/22 18:30	7/29/22 18:30	24.00
65	7/28/22 18:30	7/29/22 18:30	24.00
66	7/28/22 18:30	7/29/22 18:30	24.00
67	7/28/22 18:30	7/29/22 18:30	24.00
68	7/28/22 18:30	7/29/22 18:30	24.00
69	7/28/22 18:30	7/29/22 18:30	24.00
70	7/28/22 18:30	7/29/22 18:30	24.00
71	8/1/22 10:30	8/2/22 10:30	24.00

72	8/1/22 10:30	8/2/22 10:30	24.00
73	8/1/22 10:30	8/2/22 10:30	24.00
74	8/1/22 10:30	8/2/22 10:30	24.00
75	8/1/22 10:30	8/2/22 10:30	24.00
76	8/1/22 10:30	8/2/22 10:30	24.00
77	8/1/22 10:30	8/2/22 10:30	24.00
78	8/1/22 10:30	8/2/22 10:30	24.00
79	8/1/22 10:30	8/2/22 10:30	24.00
80	8/1/22 10:30	8/2/22 10:30	24.00
81	8/1/22 10:30	8/2/22 10:30	24.00
82	8/1/22 10:30	8/2/22 10:30	24.00
83	8/1/22 10:30	8/2/22 10:30	24.00
84	8/1/22 10:30	8/2/22 10:30	24.00
85	8/1/22 10:30	8/2/22 10:30	24.00
86	8/1/22 10:30	8/2/22 10:30	24.00
87	8/1/22 10:30	8/2/22 10:30	24.00
88	8/1/22 10:30	8/2/22 10:30	24.00
89	8/1/22 10:30	8/2/22 10:30	24.00
90	8/1/22 10:30	8/2/22 10:30	24.00
91	8/3/22 13:00	8/4/22 11:55	22.92
92	8/3/22 13:00	8/4/22 11:55	22.92
93	8/3/22 13:00	8/4/22 11:55	22.92
94	8/3/22 13:00	8/4/22 11:55	22.92
95	8/3/22 13:00	8/4/22 11:55	22.92
96	8/3/22 13:00	8/4/22 11:55	22.92
97	8/3/22 13:00	8/4/22 11:55	22.92
98	8/3/22 13:00	8/4/22 11:55	22.92
99	8/3/22 13:00	8/4/22 11:55	22.92
100	8/3/22 13:00	8/4/22 11:55	22.92
101	8/3/22 13:00	8/4/22 11:55	22.92
102	8/3/22 13:00	8/4/22 11:55	22.92
103	8/3/22 13:00	8/4/22 11:55	22.92
104	8/3/22 13:00	8/4/22 11:55	22.92
105	8/3/22 13:00	8/4/22 11:55	22.92
106	8/3/22 13:00	8/4/22 11:55	22.92
107	8/3/22 13:00	8/4/22 11:55	22.92
108	8/3/22 13:00	8/4/22 11:55	22.92
109	8/3/22 13:00	8/4/22 11:55	22.92
110	8/3/22 13:00	8/4/22 11:55	22.92
111	8/17/22 21:00	8/18/22 21:00	24.00
112	8/17/22 21:00	8/18/22 21:00	24.00
113	8/17/22 21:00	8/18/22 21:00	24.00
114	8/17/22 21:00	8/18/22 21:00	24.00
115	8/17/22 21:00	8/18/22 21:00	24.00

116	8/17/22 21:00	8/18/22 21:00	24.00
117	8/17/22 21:00	8/18/22 21:00	24.00
118	8/17/22 21:00	8/18/22 21:00	24.00
119	8/17/22 21:00	8/18/22 21:00	24.00
120	8/17/22 21:00	8/18/22 21:00	24.00
121	8/17/22 21:00	8/18/22 21:00	24.00
122	8/17/22 21:00	8/18/22 21:00	24.00
123	8/17/22 21:00	8/18/22 21:00	24.00
124	8/17/22 21:00	8/18/22 21:00	24.00
125	8/17/22 21:00	8/18/22 21:00	24.00
126	8/17/22 21:00	8/18/22 21:00	24.00
127	8/17/22 21:00	8/18/22 21:00	24.00
128	8/17/22 21:00	8/18/22 21:00	24.00
129	8/17/22 21:00	8/18/22 21:00	24.00
130	8/17/22 21:00	8/18/22 21:00	24.00

Table C3. The evaporation start and end times, and total number of hours held at 85˚C for each individual C138A unit.

UNIT	EVAPORATION START	EVAPORATION END	TOTAL TIME (HOURS)
1	1/5/24 17:00	1/6/24 17:00	24.00
2	1/5/24 17:00	1/6/24 17:00	24.00
3	1/5/24 17:00	1/6/24 17:00	24.00
4	1/5/24 17:00	1/6/24 17:00	24.00
5	1/5/24 17:00	1/6/24 17:00	24.00
6	1/5/24 17:00	1/6/24 17:00	24.00
7	1/5/24 17:00	1/6/24 17:00	24.00
8	1/5/24 17:00	1/6/24 17:00	24.00
9	1/5/24 17:00	1/6/24 17:00	24.00
10	1/5/24 17:00	1/6/24 17:00	24.00
11	1/5/24 17:00	1/6/24 17:00	24.00
12	1/5/24 17:00	1/6/24 17:00	24.00
13	1/5/24 17:00	1/6/24 17:00	24.00
14	1/5/24 17:00	1/6/24 17:00	24.00
15	1/5/24 17:00	1/6/24 17:00	24.00
16	1/9/24 12:00	1/10/24 12:00	24.00
17	1/9/24 12:00	1/10/24 12:00	24.00
18	1/9/24 12:00	1/10/24 12:00	24.00
19	1/9/24 12:00	1/10/24 12:00	24.00
20	1/9/24 12:00	1/10/24 12:00	24.00
21	1/9/24 12:00	1/10/24 12:00	24.00
22	1/9/24 12:00	1/10/24 12:00	24.00

23	1/9/24 12:00	1/10/24 12:00	24.00
24	1/9/24 12:00	1/10/24 12:00	24.00
25	1/9/24 12:00	1/10/24 12:00	24.00
26	1/9/24 12:00	1/10/24 12:00	24.00
27	1/9/24 12:00	1/10/24 12:00	24.00
28	1/9/24 12:00	1/10/24 12:00	24.00
29	1/9/24 12:00	1/10/24 12:00	24.00
30	1/9/24 12:00	1/10/24 12:00	24.00
31	1/9/24 12:00	1/10/24 12:00	24.00
32	1/9/24 12:00	1/10/24 12:00	24.00
33	1/9/24 12:00	1/10/24 12:00	24.00
34	1/9/24 12:00	1/10/24 12:00	24.00
35	1/9/24 12:00	1/10/24 12:00	24.00
36	1/12/24 18:30	1/13/24 18:30	24.00
37	1/12/24 18:30	1/13/24 18:30	24.00
38	1/12/24 18:30	1/13/24 18:30	24.00
39	1/12/24 18:30	1/13/24 18:30	24.00
40	1/12/24 18:30	1/13/24 18:30	24.00
41	1/12/24 18:30	1/13/24 18:30	24.00
42	1/12/24 18:30	1/13/24 18:30	24.00
43	1/12/24 18:30	1/13/24 18:30	24.00
44	1/12/24 18:30	1/13/24 18:30	24.00
45	1/12/24 18:30	1/13/24 18:30	24.00
46	1/12/24 18:30	1/13/24 18:30	24.00
47	1/12/24 18:30	1/13/24 18:30	24.00
48	1/12/24 18:30	1/13/24 18:30	24.00
49	1/12/24 18:30	1/13/24 18:30	24.00
50	1/12/24 18:30	1/13/24 18:30	24.00
51	1/12/24 18:30	1/13/24 18:30	24.00
52	1/12/24 18:30	1/13/24 18:30	24.00
53	1/12/24 18:30	1/13/24 18:30	24.00
54	1/12/24 18:30	1/13/24 18:30	24.00
55	1/12/24 18:30	1/13/24 18:30	24.00
56	1/17/24 12:30	1/18/24 12:30	24.00
57	1/17/24 12:30	1/18/24 12:30	24.00
58	1/17/24 12:30	1/18/24 12:30	24.00
59	1/17/24 12:30	1/18/24 12:30	24.00
60	1/17/24 12:30	1/18/24 12:30	24.00
61	1/17/24 12:30	1/18/24 12:30	24.00
62	1/17/24 12:30	1/18/24 12:30	24.00
63	1/17/24 12:30	1/18/24 12:30	24.00
64	1/17/24 12:30	1/18/24 12:30	24.00
65	1/17/24 12:30	1/18/24 12:30	24.00
66	1/17/24 12:30	1/18/24 12:30	24.00

67	1/17/24 12:30	1/18/24 12:30	24.00
68	1/17/24 12:30	1/18/24 12:30	24.00
69	1/17/24 12:30	1/18/24 12:30	24.00
70	1/17/24 12:30	1/18/24 12:30	24.00
71	1/17/24 12:30	1/18/24 12:30	24.00
72	1/17/24 12:30	1/18/24 12:30	24.00
73	1/17/24 12:30	1/18/24 12:30	24.00
74	1/17/24 12:30	1/18/24 12:30	24.00
75	1/17/24 12:30	1/18/24 12:30	24.00
76	1/19/24 12:00	1/20/24 12:00	24.00
77	1/19/24 12:00	1/20/24 12:00	24.00
78	1/19/24 12:00	1/20/24 12:00	24.00
79	1/19/24 12:00	1/20/24 12:00	24.00
80	1/19/24 12:00	1/20/24 12:00	24.00
81	1/19/24 12:00	1/20/24 12:00	24.00
82	1/19/24 12:00	1/20/24 12:00	24.00
83	1/19/24 12:00	1/20/24 12:00	24.00
84	1/19/24 12:00	1/20/24 12:00	24.00
85	1/19/24 12:00	1/20/24 12:00	24.00
86	1/19/24 12:00	1/20/24 12:00	24.00
87	1/19/24 12:00	1/20/24 12:00	24.00
88	1/19/24 12:00	1/20/24 12:00	24.00
89	1/19/24 12:00	1/20/24 12:00	24.00
90	1/19/24 12:00	1/20/24 12:00	24.00
91	1/19/24 12:00	1/20/24 12:00	24.00
92	1/19/24 12:00	1/20/24 12:00	24.00
93	1/19/24 12:00	1/20/24 12:00	24.00
94	1/19/24 12:00	1/20/24 12:00	24.00
95	1/22/24 12:00	1/23/24 12:00	24.00
96	1/22/24 12:00	1/23/24 12:00	24.00
97	1/22/24 12:00	1/23/24 12:00	24.00
98	1/22/24 12:00	1/23/24 12:00	24.00
99	1/22/24 12:00	1/23/24 12:00	24.00
100	1/22/24 12:00	1/23/24 12:00	24.00
101	1/22/24 12:00	1/23/24 12:00	24.00
102	1/22/24 12:00	1/23/24 12:00	24.00
103	1/22/24 12:00	1/23/24 12:00	24.00
104	1/22/24 12:00	1/23/24 12:00	24.00
105	1/22/24 12:00	1/23/24 12:00	24.00
106	1/22/24 12:00	1/23/24 12:00	24.00
107	1/22/24 12:00	1/23/24 12:00	24.00
108	1/22/24 12:00	1/23/24 12:00	24.00
109	1/22/24 12:00	1/23/24 12:00	24.00
110	1/22/24 12:00	1/23/24 12:00	24.00

111	1/22/24 12:00	1/23/24 12:00	24.00
112	1/22/24 12:00	1/23/24 12:00	24.00
113	1/22/24 12:00	1/23/24 12:00	24.00
114	1/22/24 12:00	1/23/24 12:00	24.00
115	1/23/24 12:00	1/24/24 12:00	24.00
116	1/23/24 12:00	1/24/24 12:00	24.00
117	1/23/24 12:00	1/24/24 12:00	24.00
118	1/23/24 12:00	1/24/24 12:00	24.00
119	1/23/24 12:00	1/24/24 12:00	24.00
120	1/23/24 12:00	1/24/24 12:00	24.00
121	1/23/24 12:00	1/24/24 12:00	24.00
122	1/23/24 12:00	1/24/24 12:00	24.00
123	1/23/24 12:00	1/24/24 12:00	24.00
124	1/23/24 12:00	1/24/24 12:00	24.00
125	1/23/24 12:00	1/24/24 12:00	24.00
126	1/23/24 12:00	1/24/24 12:00	24.00
127	1/23/24 12:00	1/24/24 12:00	24.00
128	1/23/24 12:00	1/24/24 12:00	24.00
129	1/23/24 12:00	1/24/24 12:00	24.00
130	1/23/24 12:00	1/24/24 12:00	24.00