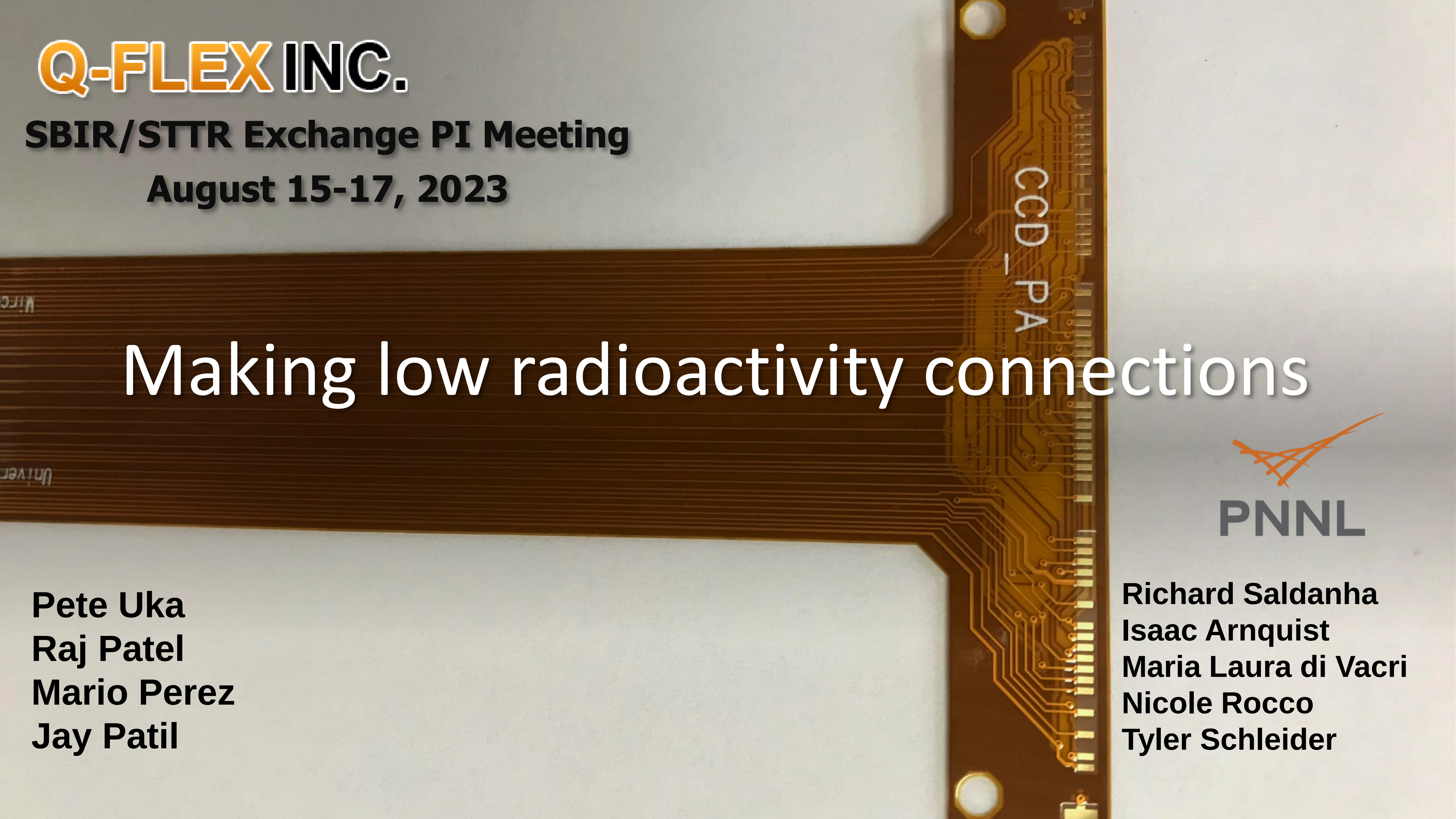


Q-FLEX INC.

SBIR/STTR Exchange PI Meeting

August 15-17, 2023

Making low radioactivity connections

Pete Uka
Raj Patel
Mario Perez
Jay Patil

PNNL

Richard Saldanha
Isaac Arnquist
Maria Laura di Vacri
Nicole Rocco
Tyler Schleider

Q-FLEX INC.

Fullerton City
California

- California based Manufacturer of Flexible circuits and Assembly with 25 years of History.

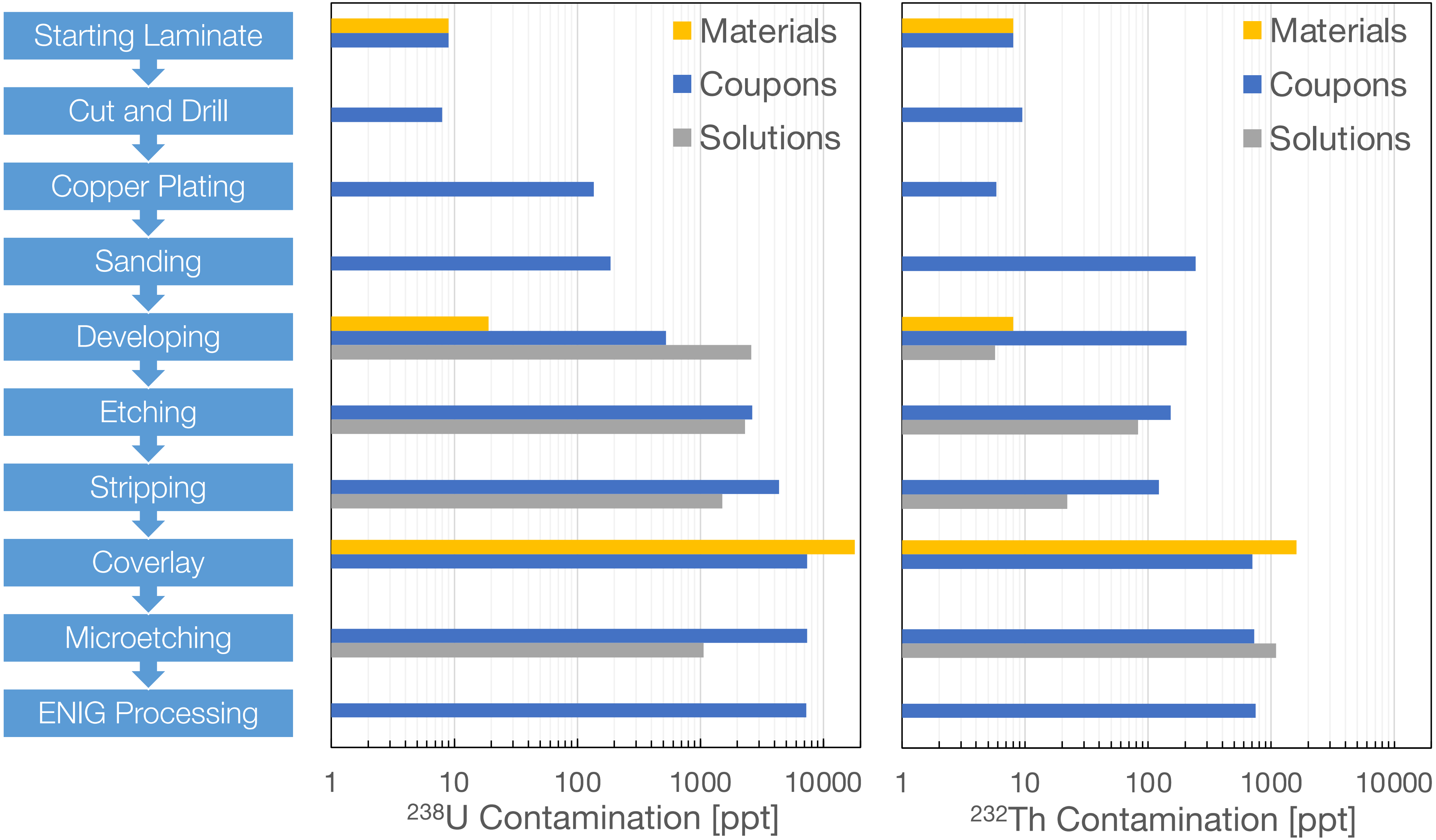
- We offer Design and Layout services- Concept to completion.
- Completed Six projects Phase I/II SBIR/STTR.

- Serving Aerospace, Medical and commercial sectors.

Q-FLEX INC.

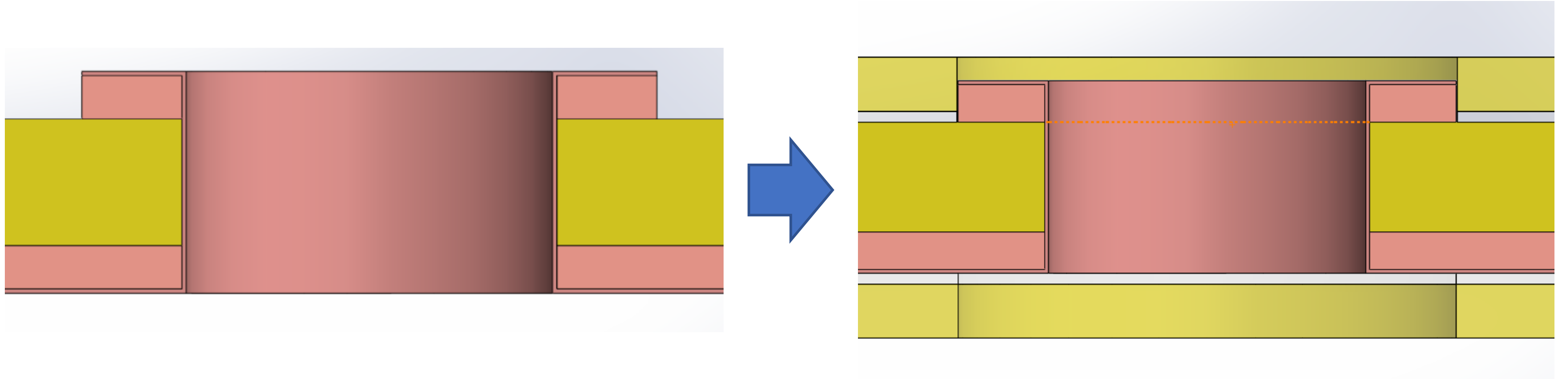
- Class 1000 cleanroom
- IPC class -3 compliance
- **Quantum Computing-** Flex with Niobium, Phosphor Bronze, Constantan, Aluminum
- **Extra long Cables**: Volume production of 2ft x 8 ft long flex. Completed 15 ft. long 4 layer flex.
- Current R & D on plating copper over Nb.
- **Low Radioactivity Cables** (This SBIR): Nuclear and High Energy Particle Physics Projects

Contamination during Fabrication



- Performed systematic assay of contamination level at each step, as well as measuring any solutions used in the process and materials added
- Final contamination levels are ~ 7000 ppt ^{238}U and ~700 ppt ^{232}Th
- Realized that there are several steps with significant increases in contamination
- Need different approach to address each issue

Coverlays



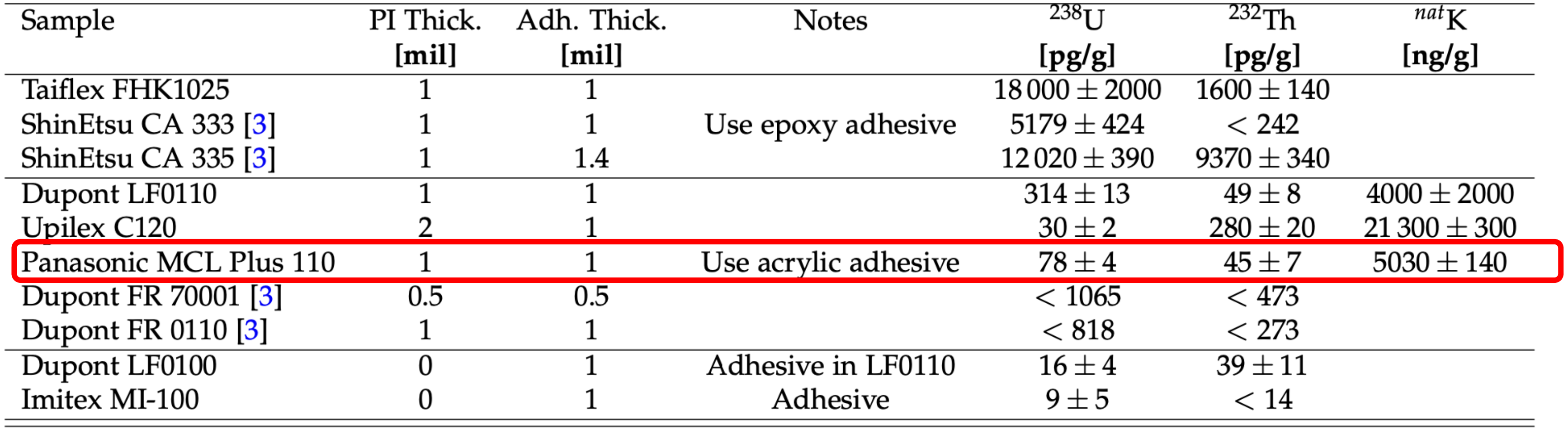
- Laminate
- Cut and Drill
- Copper Plating
- Sanding
- Developing
- Etching
- Stripping
- **Coverlay**
- Microetching
- ENIG

A coverlay is an insulating layer that is applied over the outer surfaces of a cable to prevent oxidation and shorting of the exposed traces.

Typically consists of a polyimide and adhesive layer

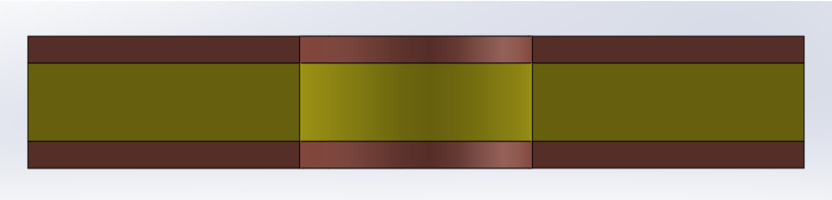
We surveyed several commercially available coverlays and found a fairly large range of contamination levels (> 100x variation in ^{238}U).

Acrylic-based adhesives were noticeably cleaner than epoxy-based adhesives.



Sample	PI Thick. [mil]	Adh. Thick. [mil]	Notes	^{238}U [pg/g]	^{232}Th [pg/g]	^{nat}K [ng/g]
Taiflex FHK1025	1	1		$18\,000 \pm 2000$	1600 ± 140	
ShinEtsu CA 333 [3]	1	1	Use epoxy adhesive	5179 ± 424	< 242	
ShinEtsu CA 335 [3]	1	1.4		$12\,020 \pm 390$	9370 ± 340	
Dupont LF0110	1	1		314 ± 13	49 ± 8	4000 ± 2000
Upilex C120	2	1		30 ± 2	280 ± 20	$21\,300 \pm 300$
Panasonic MCL Plus 110	1	1	Use acrylic adhesive	78 ± 4	45 ± 7	5030 ± 140
Dupont FR 70001 [3]	0.5	0.5		< 1065	< 473	
Dupont FR 0110 [3]	1	1		< 818	< 273	
Dupont LF0100	0	1	Adhesive in LF0110	16 ± 4	39 ± 11	
Imitex MI-100	0	1	Adhesive	9 ± 5	< 14	

Copper Plating

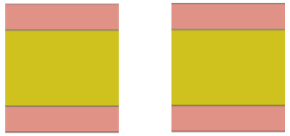


Interconnections between layers (vias) need to be plated with copper

- Laminate
- Cut and Drill
- **Copper Plating**
- Sanding
- Developing
- Etching
- Stripping
- Coverlay
- Microetching
- ENIG

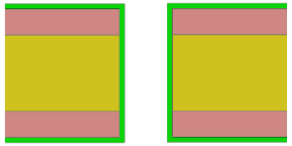
STANDARD ELECTROLESS PROCESS

Laminate + drilling



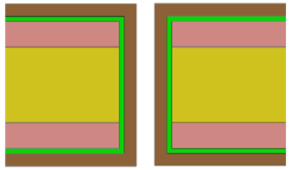
Pre-cleaning		Post-cleaning	
U [ppt]	Th [ppt]	U [ppt]	Th [ppt]
20 ± 2	5 ± 2	14 ± 3	10 ± 4

Electroless seed



Pre-cleaning		Post-cleaning	
U [ppt]	Th [ppt]	U [ppt]	Th [ppt]
170 ± 9	25 ± 10	136 ± 13	92 ± 79

Electroplating

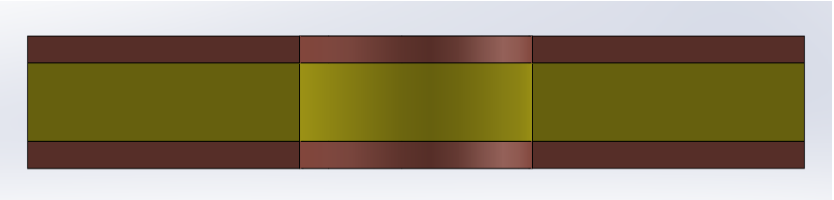


Pre-cleaning		Post-cleaning	
U [ppt]	Th [ppt]	U [ppt]	Th [ppt]
80 ± 5	10 ± 7	72 ± 4	15 ± 8

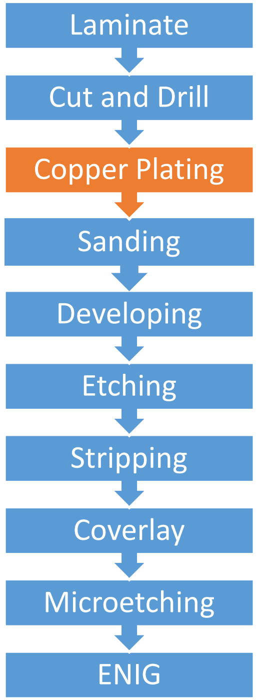
This process involves several solutions and catalysts, and both the seed and plating layers cover the entire copper surface, potentially trapping contamination

We were unable to reduce the contamination below ~ 50 ppt U through cleaning

Copper Plating



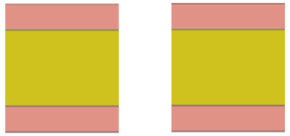
Interconnections between layers (vias)
need to be plated with copper



- Laminate
- Cut and Drill
- **Copper Plating**
- Sanding
- Developing
- Etching
- Stripping
- Coverlay
- Microetching
- ENIG

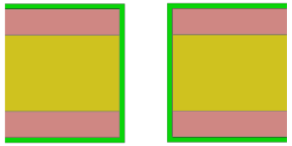
STANDARD ELECTROLESS PROCESS

Laminate + drilling



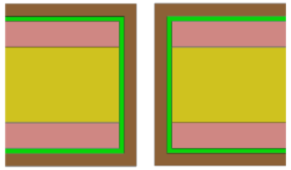
Pre-cleaning		Post-cleaning	
U [ppt]	Th [ppt]	U [ppt]	Th [ppt]
20 ± 2	5 ± 2	14 ± 3	10 ± 4

Electroless seed



Pre-cleaning		Post-cleaning	
U [ppt]	Th [ppt]	U [ppt]	Th [ppt]
170 ± 9	25 ± 10	136 ± 13	92 ± 79

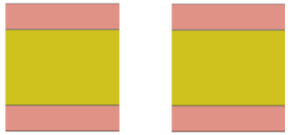
Electroplating



Pre-cleaning		Post-cleaning	
U [ppt]	Th [ppt]	U [ppt]	Th [ppt]
80 ± 5	10 ± 7	72 ± 4	15 ± 8

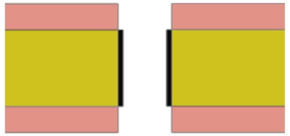
SHADOW PLATING PROCESS

Laminate + drilling



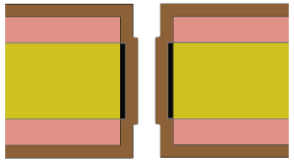
Pre-cleaning		Post-cleaning	
U [ppt]	Th [ppt]	U [ppt]	Th [ppt]
21 ± 6	12 ± 4	11 ± 5	6 ± 5

Shadow plating



Pre-cleaning		Post-cleaning	
U [ppt]	Th [ppt]	U [ppt]	Th [ppt]
60 ± 70	52 ± 10	12 ± 5	5 ± 4

Electroplating

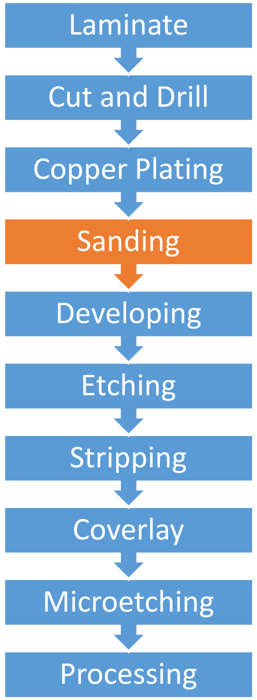


Pre-cleaning		Post-cleaning	
U [ppt]	Th [ppt]	U [ppt]	Th [ppt]
90 ± 13	8 ± 3	7 ± 3	7 ± 4

A newer alternative process to the electroless Cu step is the “shadow” process where a thin carbon layer is added only to the polyimide region and involves fewer chemicals

The resulting coupons had contamination levels consistent with the base laminate level, **roughly 6x cleaner in ^{238}U than the electroless seed process**

Sanding



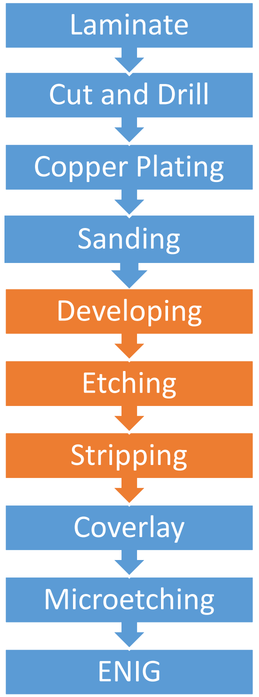
Laminate
Cut and Drill
Copper Plating
Sanding
Developing
Etching
Stripping
Coverlay
Microetching
Processing

- Prior to the application of photoresist, the cable surface is mechanically prepared for optimal film adhesion and clean release.
- The scrubbing process was found to increase ^{232}Th contamination, presumably due to the implantation of small amounts of the abrasive material into the laminate.
- Cleaning was tried but found ineffective
- Switched to only using commercial pads made from SiC, rather than previously used pads that used aluminum oxide, titanium dioxide, and other fillers and pigments.
- **This led to roughly a 10x reduction in ^{232}Th contamination after this step**

Ingredient	% by Wt
Aluminum Oxide Mineral	30-45
Nylon Fiber	20-30
Filler	5-10
Pigment	0-2.5
Titanium Dioxide	0-2.5
Silica	0-2.5
Cured Resin	20-30

Ingredient	% by Wt
Silicon Carbide Mineral	25-40
Nylon Fiber	20-35
Quartz Silica	0.05-0.2
Cured Resin	30-45
Hookit^{TM} Backing	0-10

Cleaning Results



Laminate

Cut and Drill

Copper Plating

Sanding

Developing

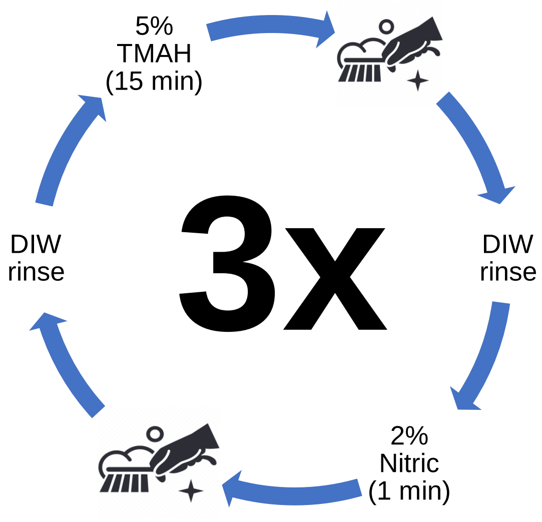
Etching

Stripping

Coverlay

Microetching

ENIG



5% TMAH (15 min)

DIW rinse

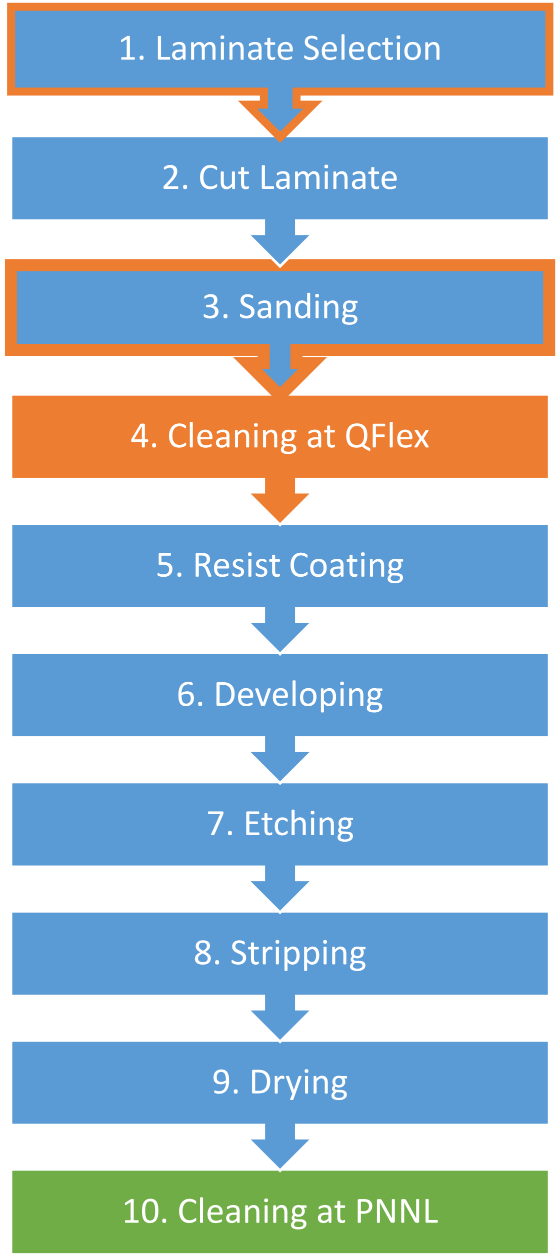
2% Nitric (1 min)

DIW rinse

3x

	^{238}U [ppt]	^{232}Th [ppt]
After Stripping Before Cleaning	6000 +/- 200	27 +/- 3
After Stripping After Cleaning	20 +/- 1.3	< 9.3

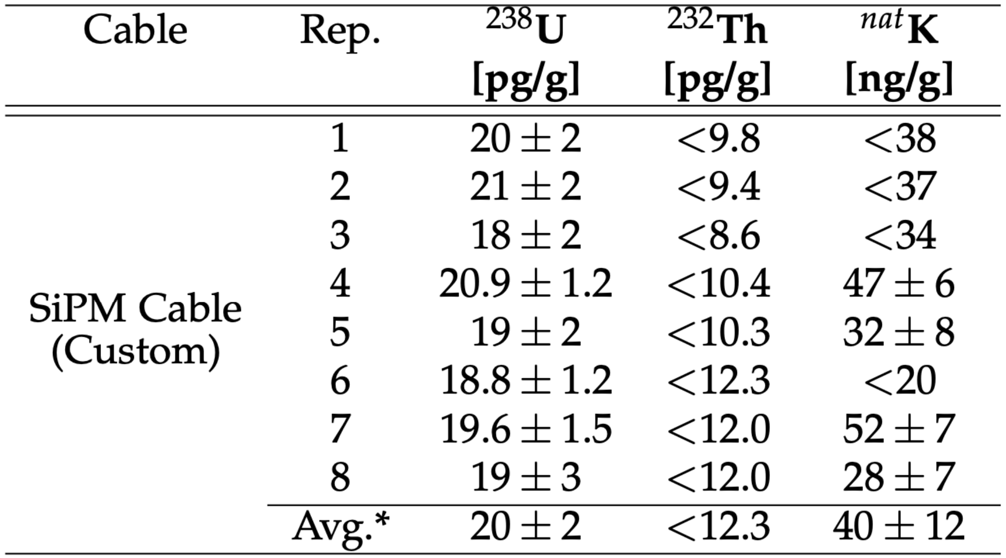
Cleaning brings contamination back down to the tens of ppt levels



1. Laminate Selection
2. Cut Laminate
3. Sanding
4. Cleaning at QFlex
5. Resist Coating
6. Developing
7. Etching
8. Stripping
9. Drying
10. Cleaning at PNNL

Blue: Standard Step
Orange Outline: Modified Step
Orange: New Step
Green: Step done at PNNL

Simple 2-layer Cable



Cable	Rep.	^{238}U [pg/g]	^{232}Th [pg/g]	^{nat}K [ng/g]
SiPM Cable (Custom)	1	20 ± 2	<9.8	<38
	2	21 ± 2	<9.4	<37
	3	18 ± 2	<8.6	<34
	4	20.9 ± 1.2	<10.4	47 ± 6
	5	19 ± 2	<10.3	32 ± 8
	6	18.8 ± 1.2	<12.3	<20
	7	19.6 ± 1.5	<12.0	52 ± 7
	8	19 ± 3	<12.0	28 ± 7
	Avg.*	20 ± 2	<12.3	40 ± 12

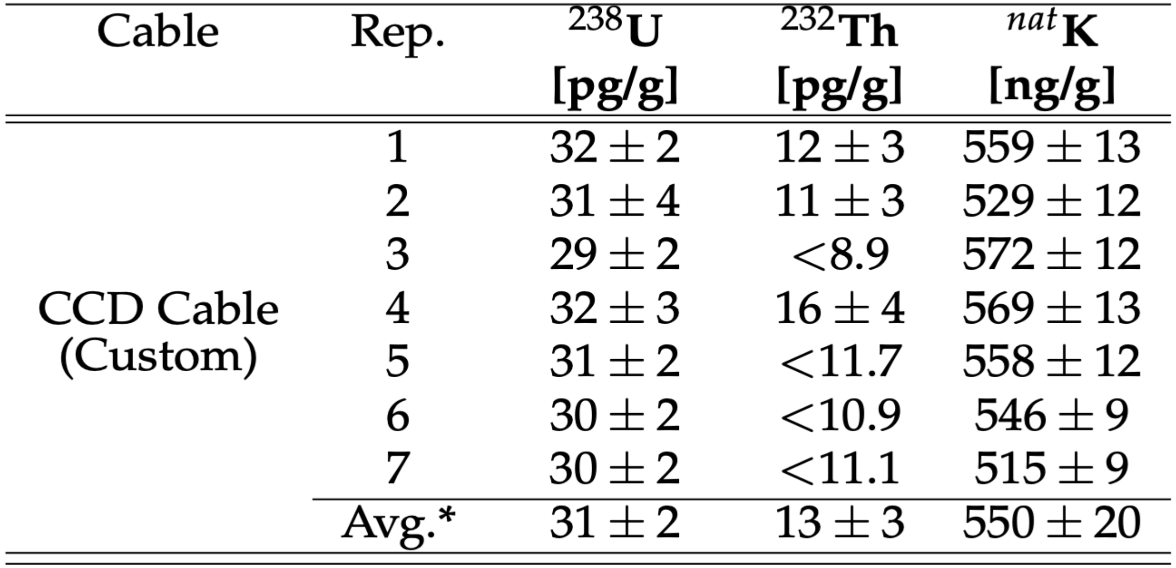
	^{238}U [ppt]	^{232}Th [ppt]
Starting Laminate	8 +/- 6	9 +/- 4
Standard Cable Trial 1 Standard Cable Trial 2	6200 +/- 100 1300 +/- 300	63 +/- 5 16 +/- 6
Our Final Cable	20 +/- 2	< 12.3

We have managed to reduce the ^{238}U contamination by > 65x

1. Laminate Selection
2. Cut and Drill Laminate
3. Cleaning at QFlex
4. Shadow Seeding
5. Electroplating
6. Sanding
7. Cleaning at PNNL
8. Resist Coating
9. Developing
10. Etching
11. Stripping
12. Drying
13. Cleaning at PNNL
14. Coverlay Application
15. Microetching
16. ENIG Processing
17. Cleaning at PNNL

Blue: Standard Step
Orange Outline: Modified Step
Orange: New Step
Green: Step done at PNNL

Full 2-layer cable



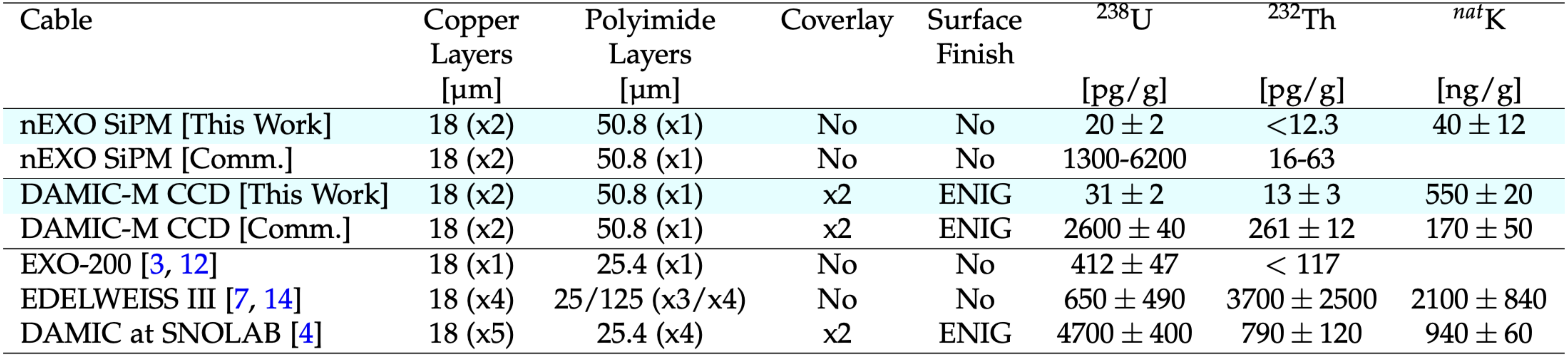
Cable	Rep.	^{238}U [pg/g]	^{232}Th [pg/g]	^{nat}K [ng/g]
CCD Cable (Custom)	1	32 ± 2	12 ± 3	559 ± 13
	2	31 ± 4	11 ± 3	529 ± 12
	3	29 ± 2	<8.9	572 ± 12
	4	32 ± 3	16 ± 4	569 ± 13
	5	31 ± 2	<11.7	558 ± 12
	6	30 ± 2	<10.9	546 ± 9
	7	30 ± 2	<11.1	515 ± 9
	Avg.*	31 ± 2	13 ± 3	550 ± 20

	^{238}U [ppt]	^{232}Th [ppt]
Commercial Cable	2600 +/- 40	261 +/- 12
Our Cable	31 +/- 2	13 +/- 3

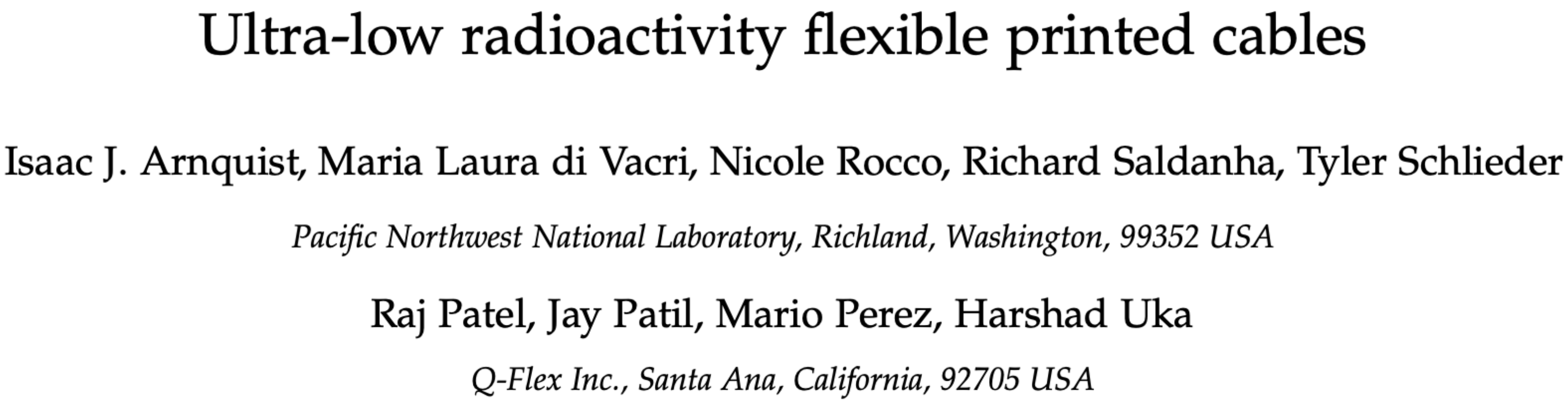
We have managed to reduce the ^{238}U contamination by ~100x, ^{232}Th by ~ 20x

Even with the addition of vias, coverlays, and ENIG, the U and Th contamination levels are at ~10's of ppt

Comparison to Literature



Cable	Copper Layers [μm]	Polyimide Layers [μm]	Coverlay	Surface Finish	^{238}U [pg/g]	^{232}Th [pg/g]	^{nat}K [ng/g]
nEXO SiPM [This Work]	18 (x2)	50.8 (x1)	No	No	20 ± 2	<12.3	40 ± 12
nEXO SiPM [Comm.]	18 (x2)	50.8 (x1)	No	No	1300-6200	16-63	
DAMIC-M CCD [This Work]	18 (x2)	50.8 (x1)	x2	ENIG	31 ± 2	13 ± 3	550 ± 20
DAMIC-M CCD [Comm.]	18 (x2)	50.8 (x1)	x2	ENIG	2600 ± 40	261 ± 12	170 ± 50
EXO-200 [3, 12]	18 (x1)	25.4 (x1)	No	No	412 ± 47	< 117	
EDELWEISS III [7, 14]	18 (x4)	25/125 (x3/x4)	No	No	650 ± 490	3700 ± 2500	2100 ± 840
DAMIC at SNOLAB [4]	18 (x5)	25.4 (x4)	x2	ENIG	4700 ± 400	790 ± 120	940 ± 60



Ultra-low radioactivity flexible printed cables

Isaac J. Arnquist, Maria Laura di Vacri, Nicole Rocco, Richard Saldanha, Tyler Schlieder

Pacific Northwest National Laboratory, Richland, Washington, 99352 USA

Raj Patel, Jay Patil, Mario Perez, Harshad Uka

Q-Flex Inc., Santa Ana, California, 92705 USA

arXiv:2303.10862

Summary

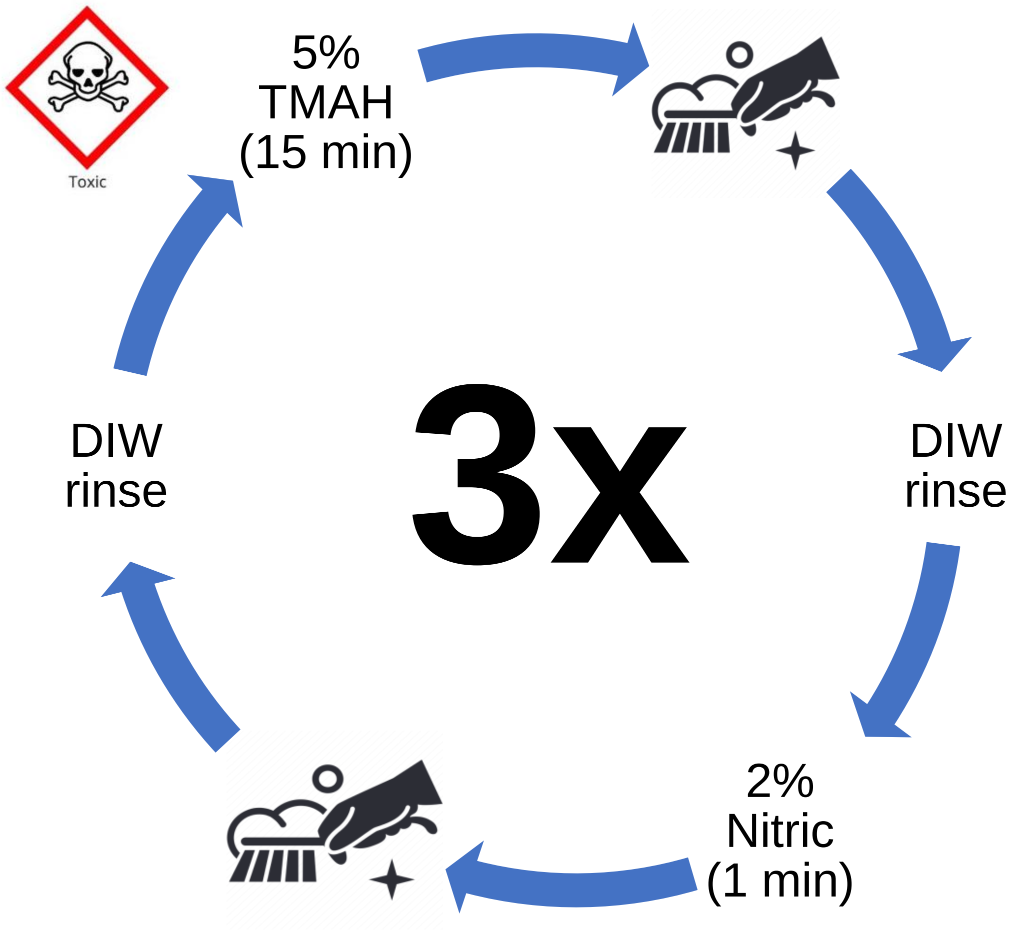
- Commercial flexible cable options are very radioactive (~1000’s of ppt ^{238}U, ~100’s of ppt ^{232}Th), limiting the use of cables in experiments

- By working closely with a commercial company and systematically investigating the fabrication process, we have identified the key sources of contamination

- Following a diverse approach of developing new cleaning steps, modifying fabrication processes, identifying radiopure raw material, and improving mechanical handling, we have **reduced the U and Th backgrounds to the level of ~ 10’s of ppt ^{238}U and ^{232}Th**

- **We have demonstrated that coverlays, vias, and ENIG metallization can be added with only small increases to the radiopurity – possibly simplifying the design and layout of low background cables**

Simplifying the Cleaning Process



5%
TMAH
(15 min)

DIW
rinse

2%
Nitric
(1 min)

DIW
rinse

3x

Replace with a simple 2 step process - Results are promising

Acknowledgements

We are extremely grateful to our national laboratory partners at PNNL for providing all the testing services as well as valuable technical guidance. We would like to specifically thank
Richard Saldanha, Isaac Arnquist, Maria Laura di Vacri, Nicole Rocco, Tyler Schleider

We would like to thank Dave Moore and the entire **nEXO collaboration** for providing the design for our “simple” cables and Alvaro Chavarria and the entire **DAMIC-M collaboration** for providing the design of the “full” cables

This work was funded by
DOE Small Business Innovations Research (Phase I 2021, Phase II 2022-2024)