Reliability Assessments of Irradiated Integrated Silicon Carbide Pressure/Temperature Sensors for Fission Surface Power Reactor

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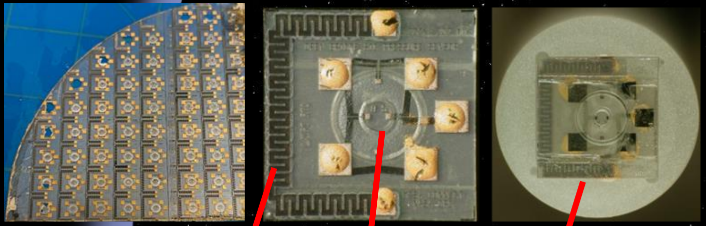
- NASA Fission Surface Power Project (Travel and Procurements)

Motivation

- NASA and DOE are developing a technology demonstration of a Lunar Fission Surface Power (FSP) reactor. Precursor to future nuclear reactor on Mars.
- Unlike typical nuclear power plants and emerging Small Modular Reactors (SMRs), the lunar FSP system is more compact, autonomous, and a prescribed 10-year life.
- Sensors and instrumentation must be compact (reduced form factor), integrated functions, rad-hard, and high temperature (~800 ℃) durable.
- Failing lunar FSP reactor sensors would not have the luxury of replacement.
- From reliability and robustness standpoint, sensor technologies currently don't exist.
- New, robust, and reliable sensor technologies are needed for FSPs and SMRs.

Pressure Sensor Key Performance Parameters

On-Chip integrated SiC P/T (RTD) sensors



$$V(T, P) = V_{ZPO}(T) + S(T)P$$

Zero Pressure Offset Voltage	Pressure Sensitivity (Gauge Factor)

- Stability of these parameters determine sensor measurement reliability and accuracy.
- Combined variables make analysis more complex.
- De-Coupling needed for effective analysis.

This presentation

ZPO/RTD Only (NSUF – RTE)(OSU)

$$V(T, n, \gamma) = V_{ZPO}(T, n, \gamma)$$

ZPO/RTD and S: P, T, n, γ (Super RTE at MIT)

$$V(T, P, n, \gamma) = V_{ZPO}(T, n, \gamma) + S(T, n, \gamma)P$$

Package-embedded TC

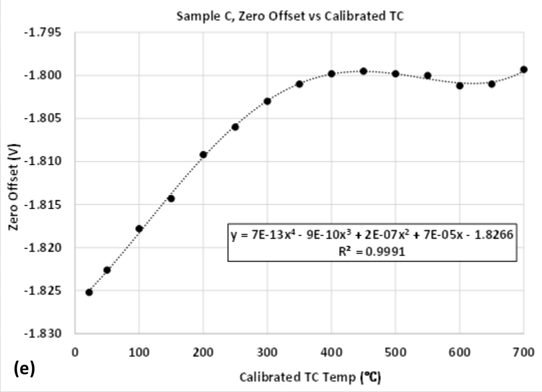
P/T (RTD)

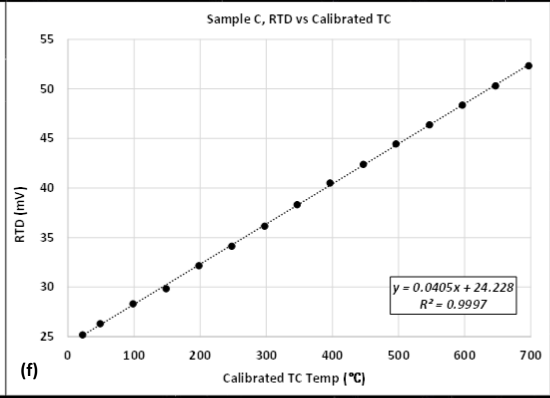
Fully Packaged SiC P/T Transducer

ZPO and RTD Oven Characterization

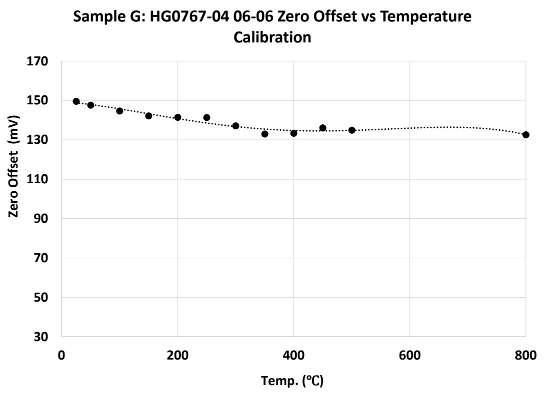
ZPO Characteristics RTD Characteristics

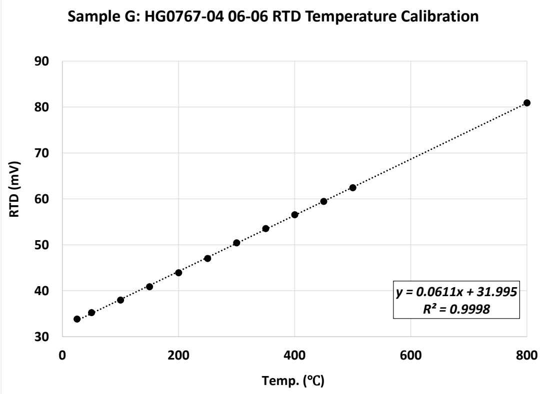
Sample C (T, n, γ)





Sample G [T (500 C), n, γ]





Each sensor has its unique characteristics, hence calibrated individually

Performance Parametrics

CRS=Cumulative Relative Shift across aggregate cycles

RS=Relative Shift after each cycle

$$CRS = \frac{ZPO(t) - ZPO_{pre-irradiation}}{ZPO_{pre-irradiation}} x100\ \%$$

$$RS = \frac{ZPO(t) - ZPO_{initial}}{ZPO_{initial}} x100\ \%$$

Note:

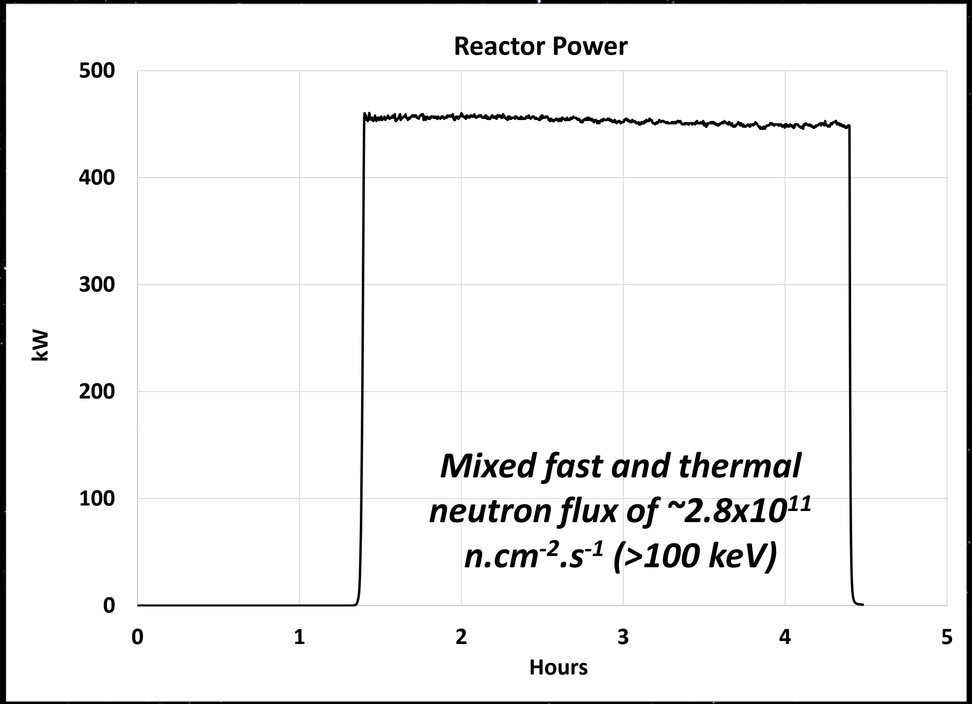
Oven characterized ZPO and RTD values tend to change with new cable harness before irradiation. New pre-irradiation values (before reactor power on) were applied to quantify performance parameters

Test Setup

Sample #	Doping Conc. (cm^{-3})	Total Fluence ($n\text{-}cm^{-2}$)	Total Minimum Gamma (Mrad)	Cumulative Time (hrs)
A	10^{19}	~1.22×10^{16}	88	12.1
B	10^{19}	~1.12×10^{16}	80	11
C	10^{19}	~2.22×10^{16}	160	22
G (500 ℃)	10^{19}	~2.24×10^{16}	160	22.2

Samples A, B, and D from same wafer

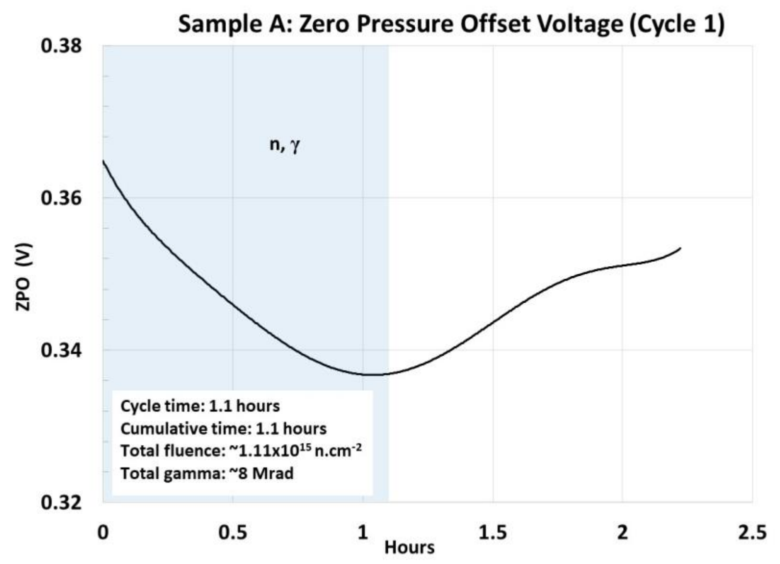
Fully assembled integrated pressure/temperature sensors with facility reference TCs ready

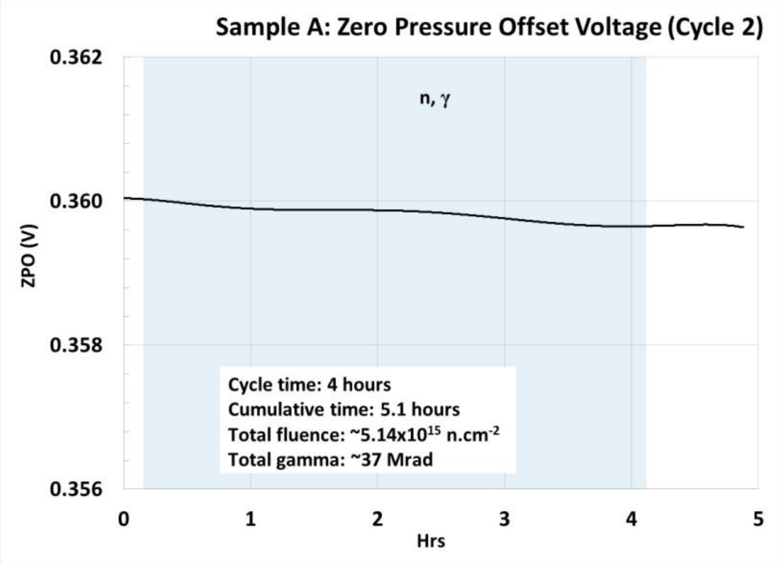


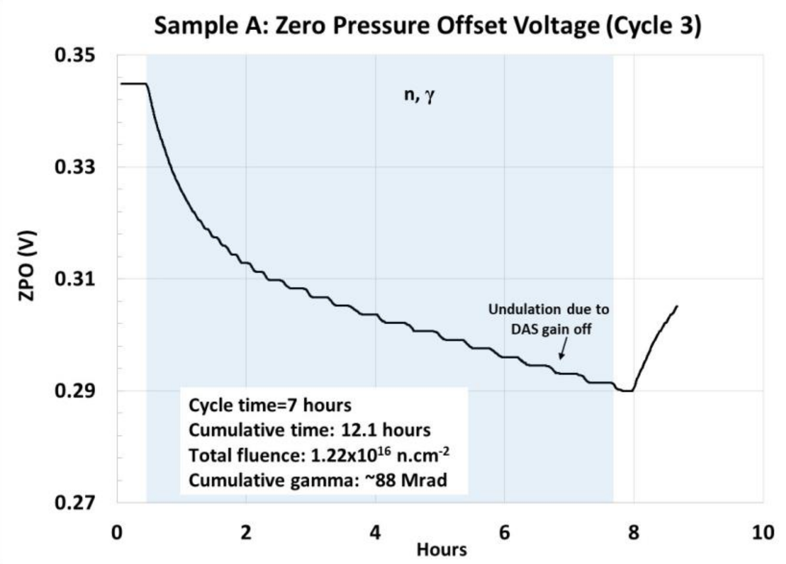
Typical reactor power profile used during irradiation

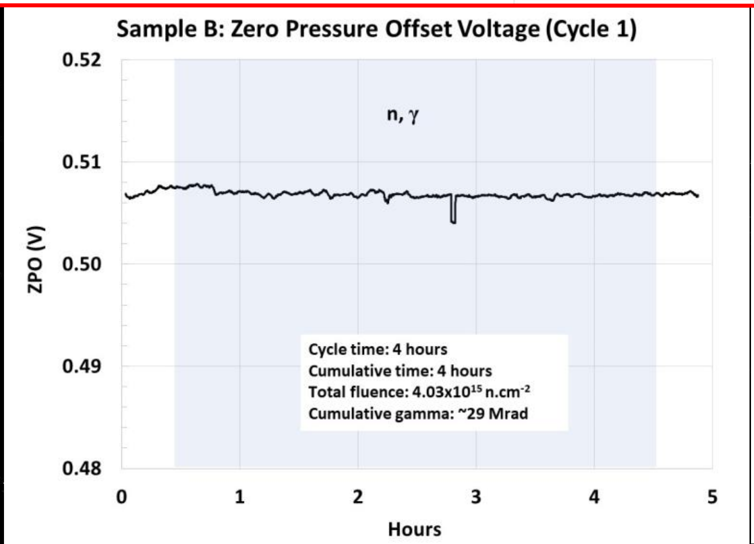
Pressure Sensor ZPO Response

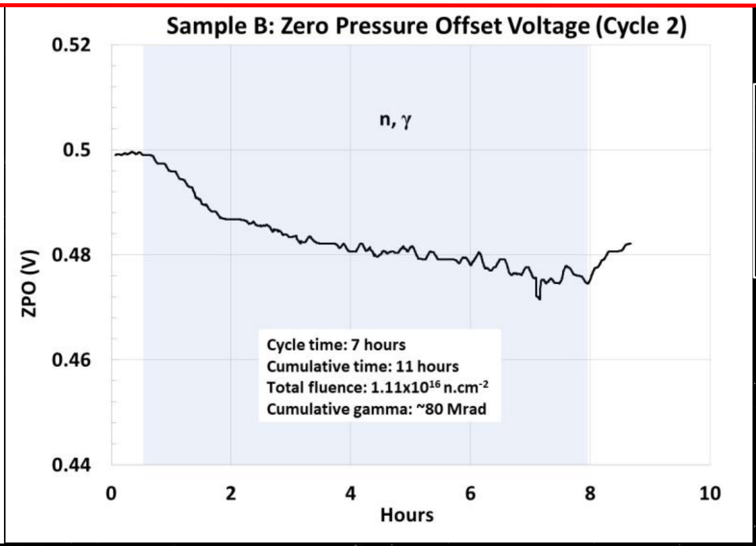
(Samples A and B)









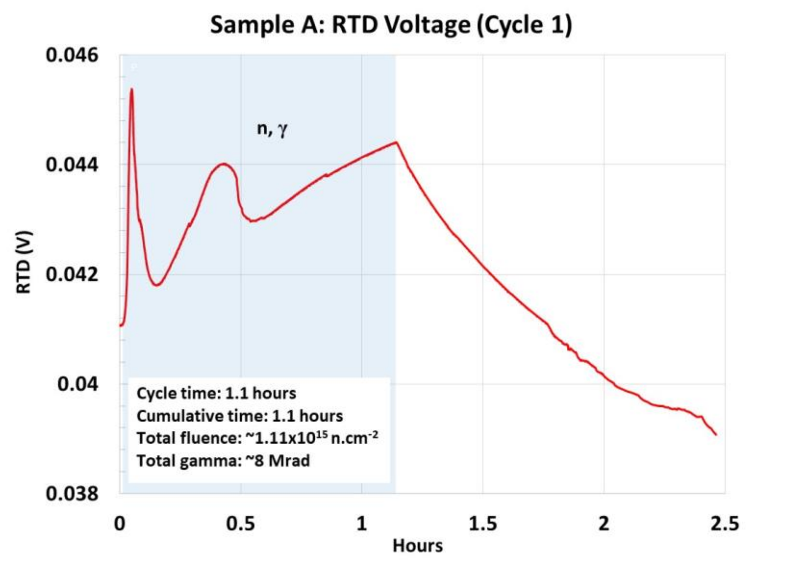


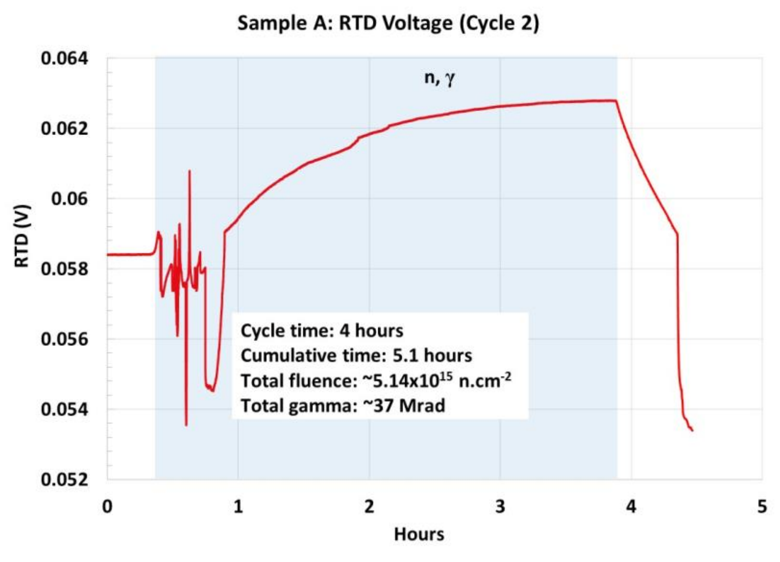
- ZPO trending toward pre-irradiation values.
- Small and large drifts.

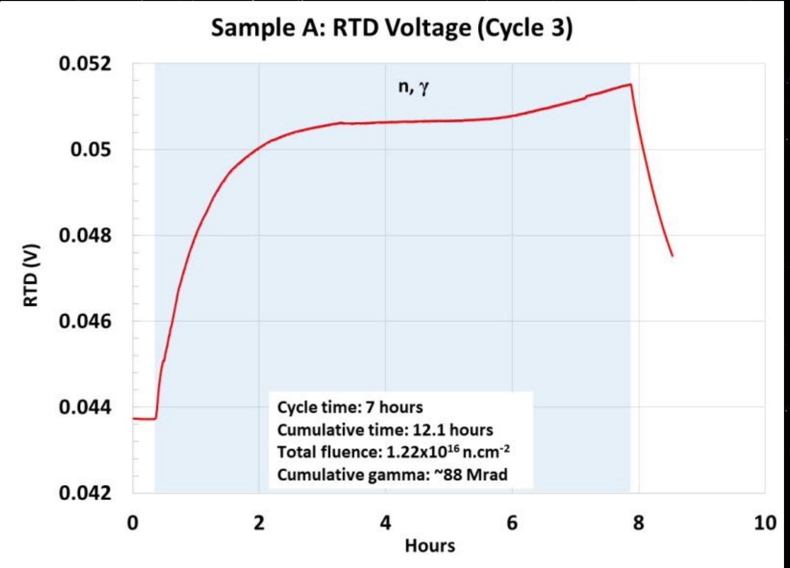
On-Chip Integrated RTD Response

(Samples A and B)

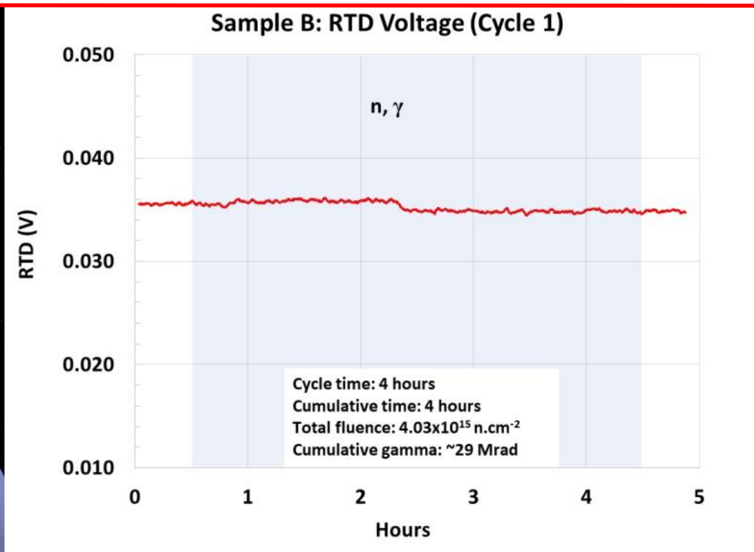
Sample-A

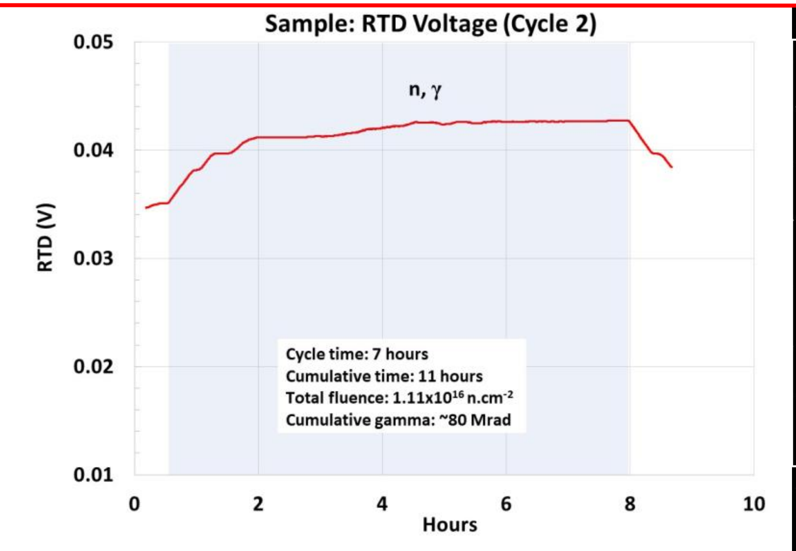






Sample-B



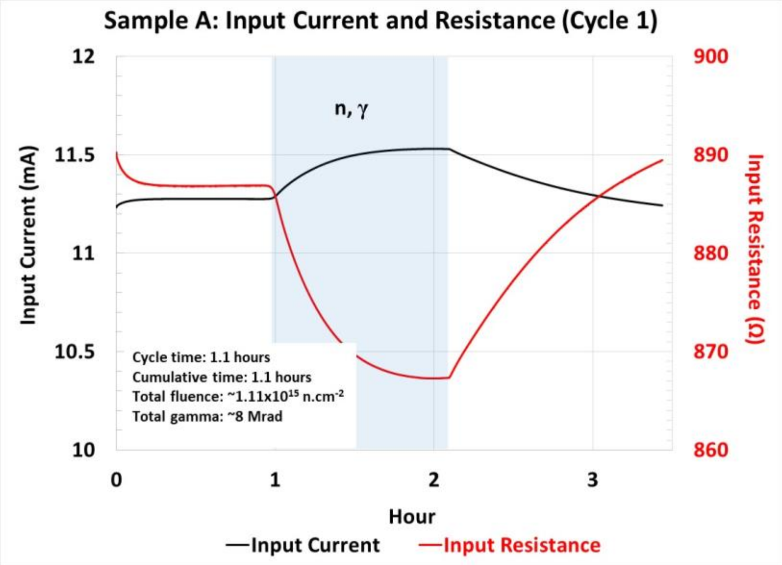


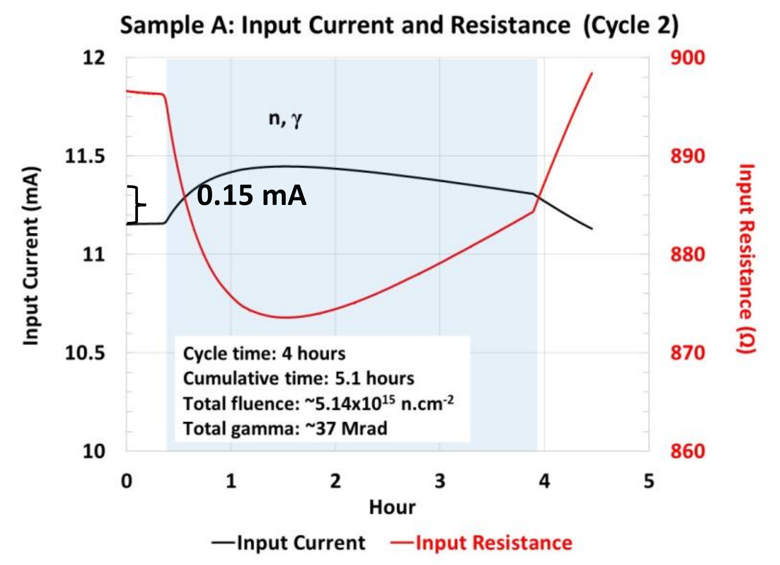
- **Sample A: Breakdown of non-radhard plastic insulation. Replaced on subsequent samples.**
- **Other than Cycle 2 of Sample A, both samples trended toward pre-irradiation values.**
- **Small drifts in B; large drifts in A.**

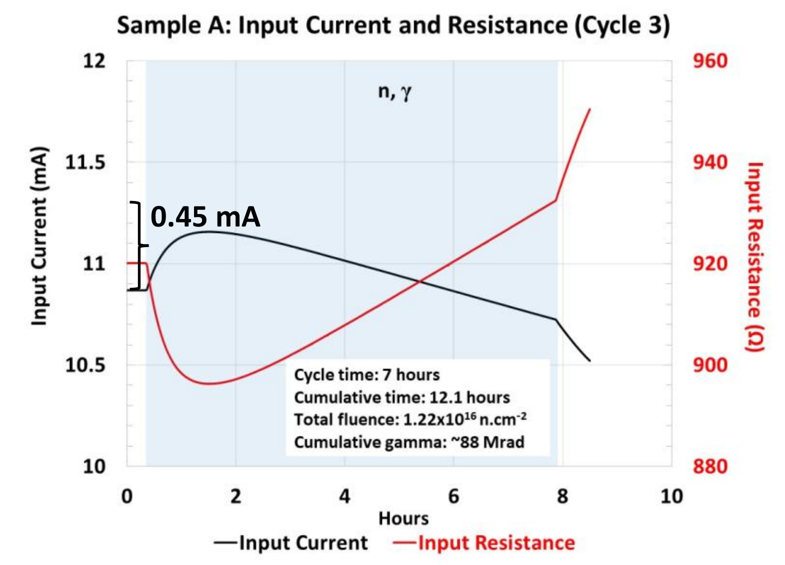
Pressure Sensors Input Current Response

(Samples A and B)

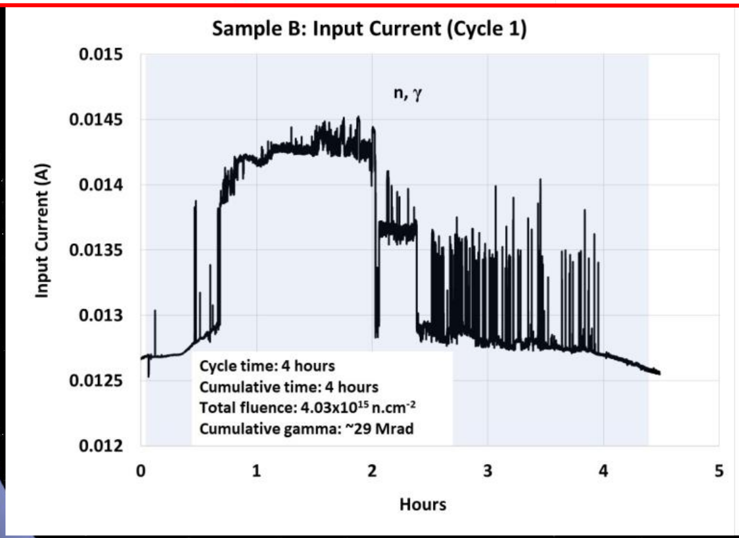
Sample-A

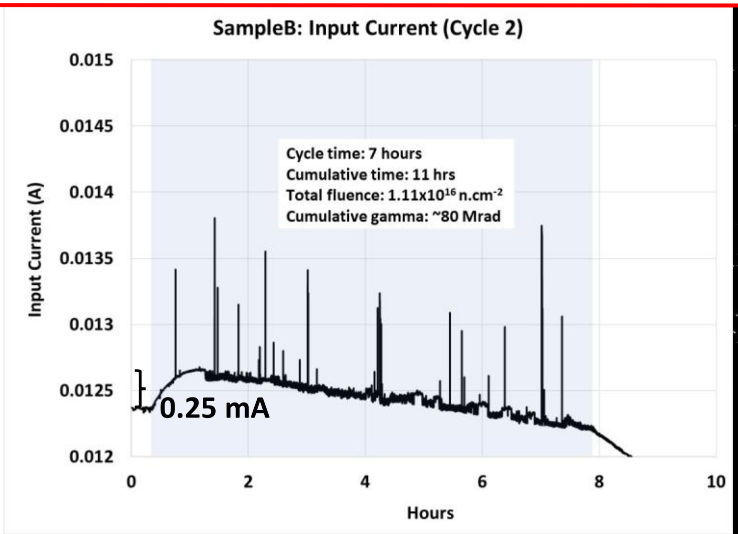






Sample-B

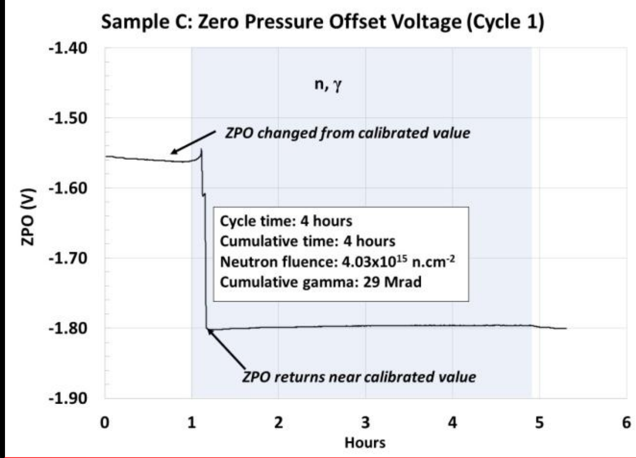


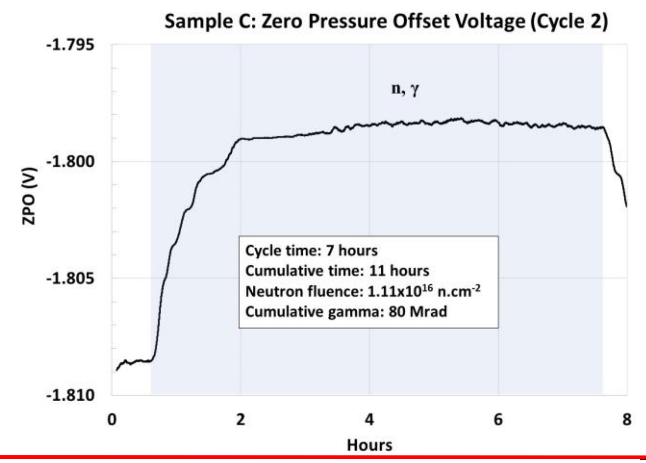


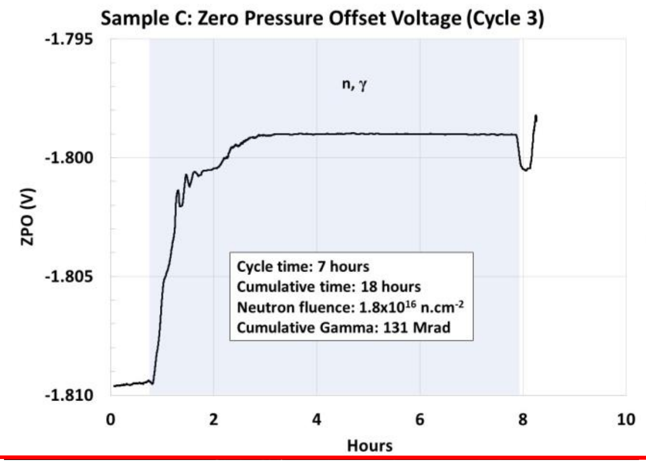
- Parabolic rise and linear decrease of current.
- Current reduced after each cycle.
- Spikes in B likely unstable contacts.
- Sample B: Large parabolic current drop. O/P instability recorded during oven calibration.

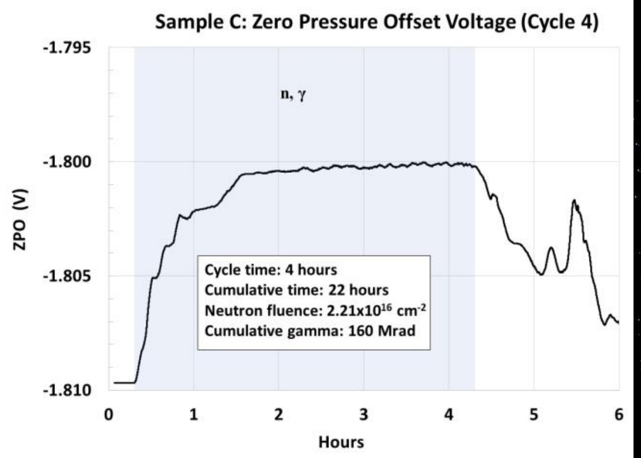
Pressure Sensor ZPO Response

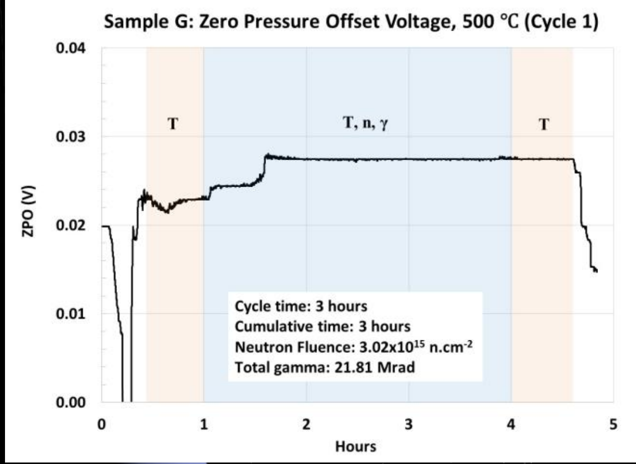
Comparison: Samples C (unheated) and G (500 ^oC)

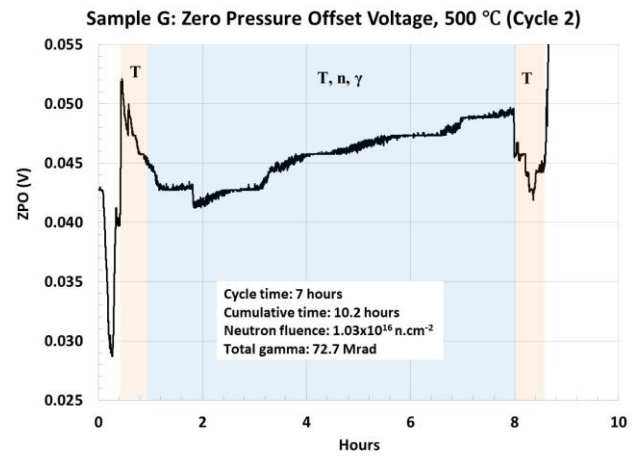


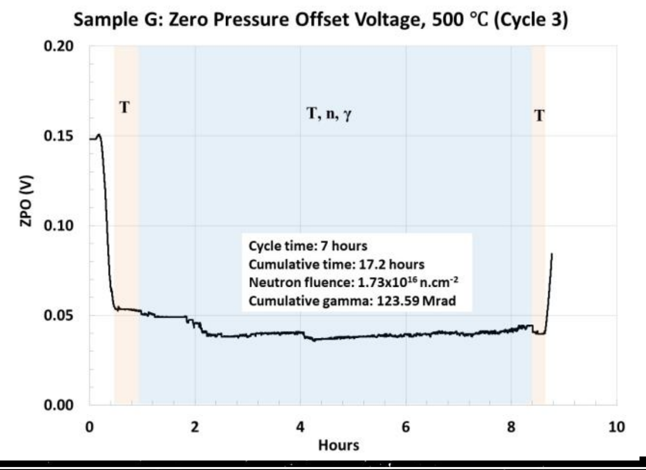


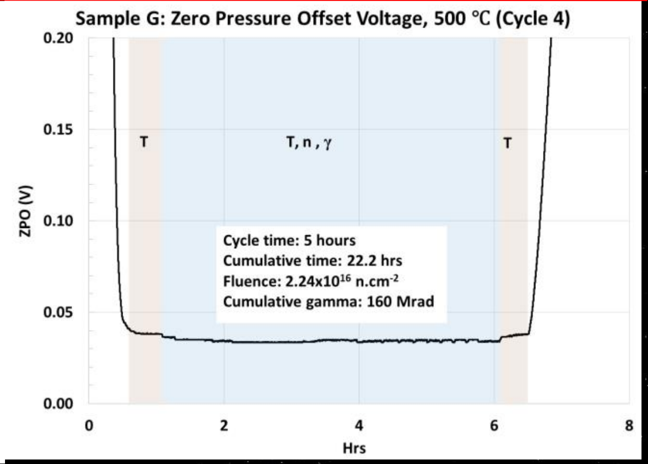








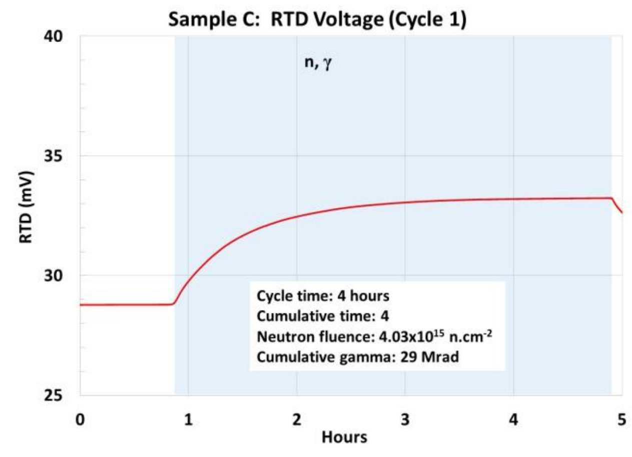


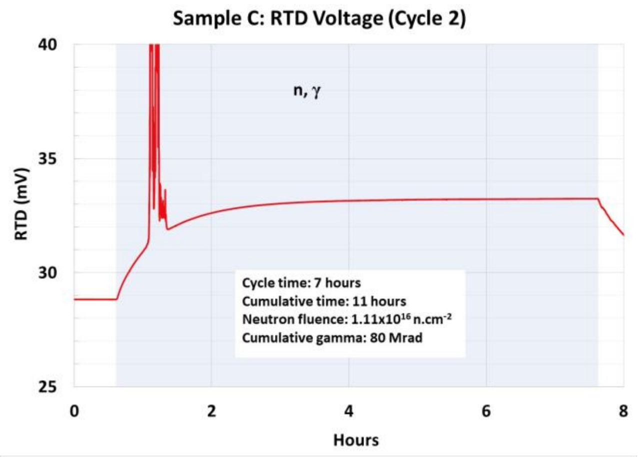


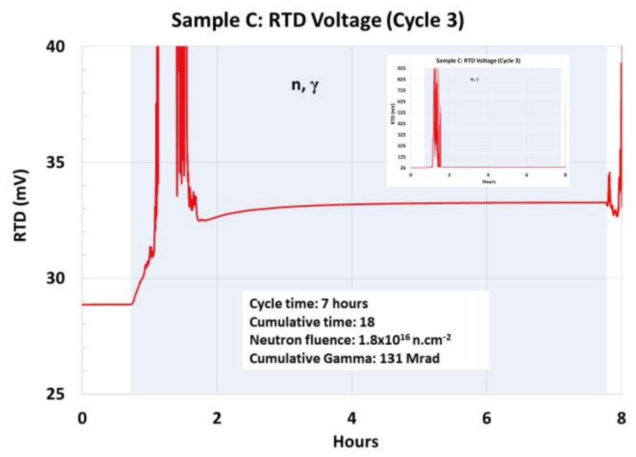
- **Sample C ZPO trended toward pre-irradiation value by start of next cycle.**
- **ZPO remained relatively stable in steady state range. Large drifts seen in Sample G.**
- **Large drift in Cycle 2 of Sample G (500 ℃) yet to be understood. Contact metallization suspected.**
- **Shift in pre-irradiation ZPO values likely due to wiring assembly.**

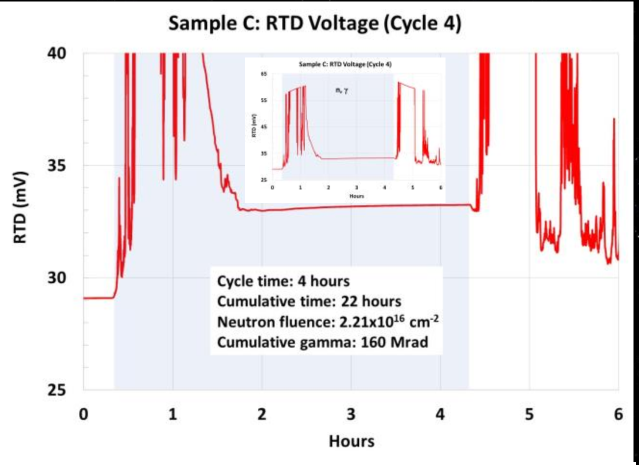
On-Chip Integrated RTD Response

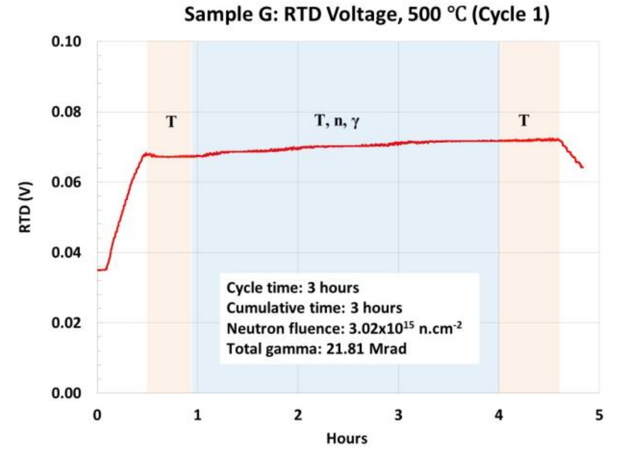
Comparison: Samples C (unheated) and G (500 ^oC)

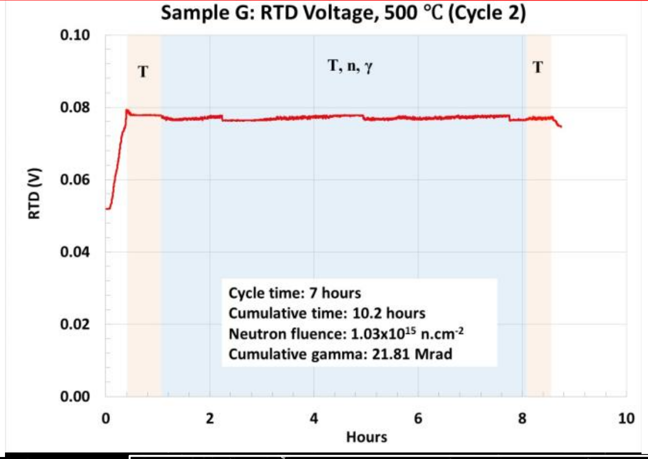


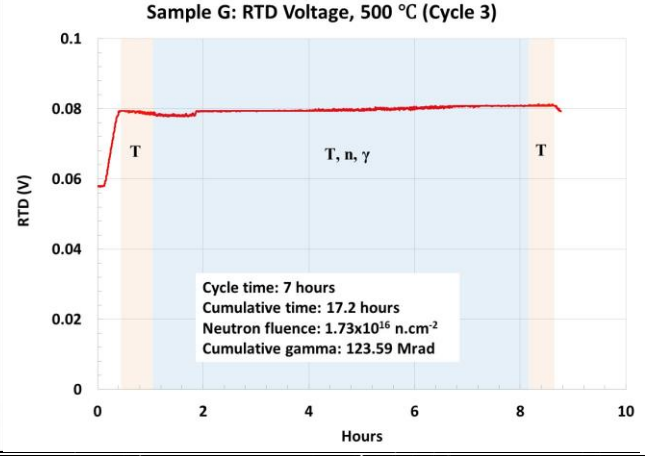


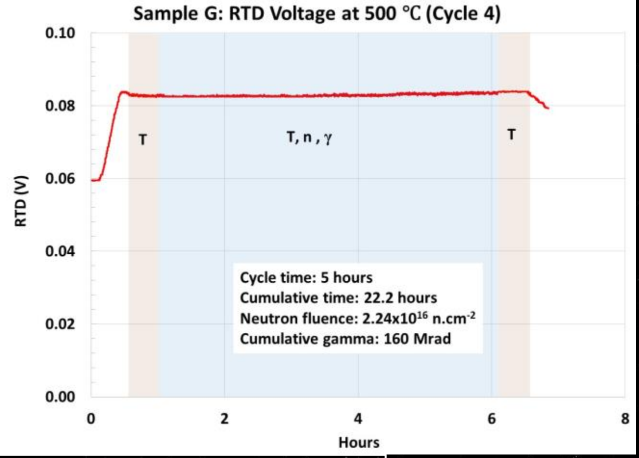








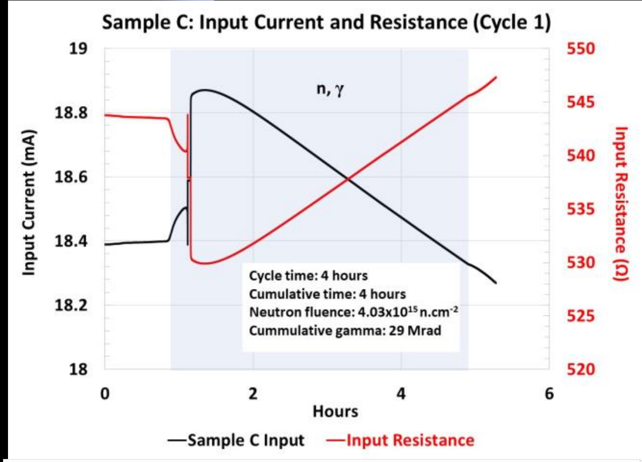


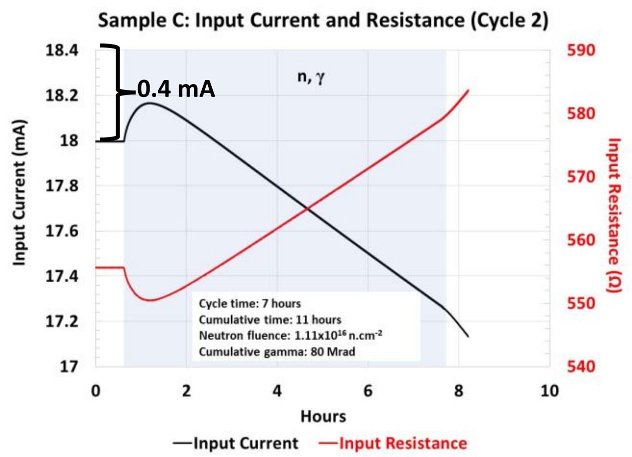


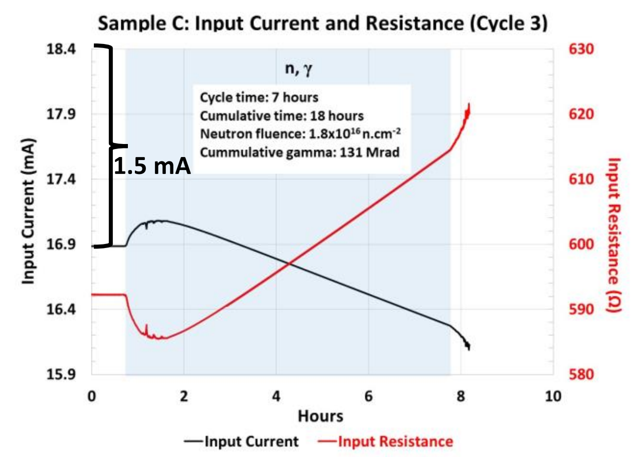
- **Sample C: instability before and after irradiation-possibly γ-induced oxide charging increasing with higher gamma dose.**
- **Phenomenon not seen in the sample G 500 C runs: In-situ annealing?**
- **RTD voltage trending toward pre-irradiation value by start of next cycle.**
- **RTD voltage remained relatively steady in operational range, with some drifts.**

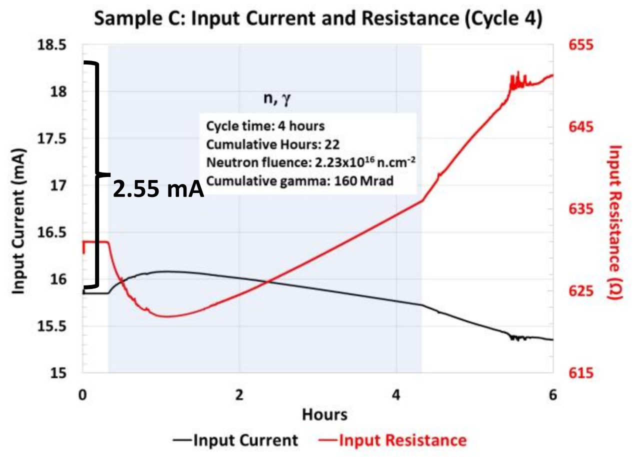
Pressure Sensor Input Current Response

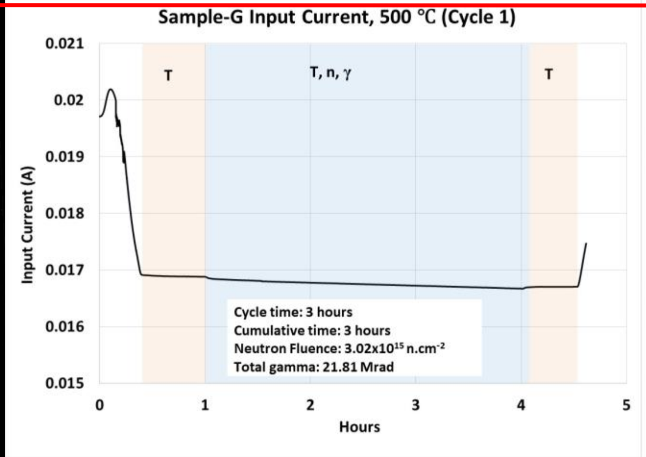
Comparison: Samples C (unheated) and G (500 ^oC)

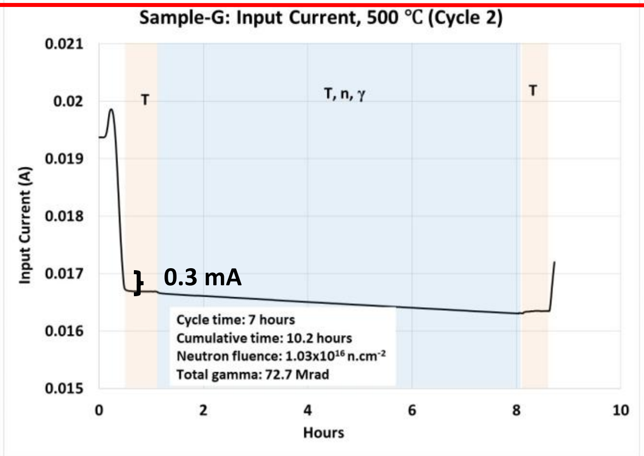


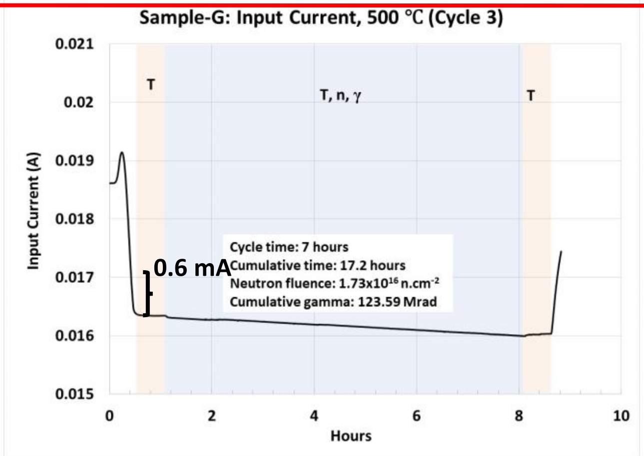


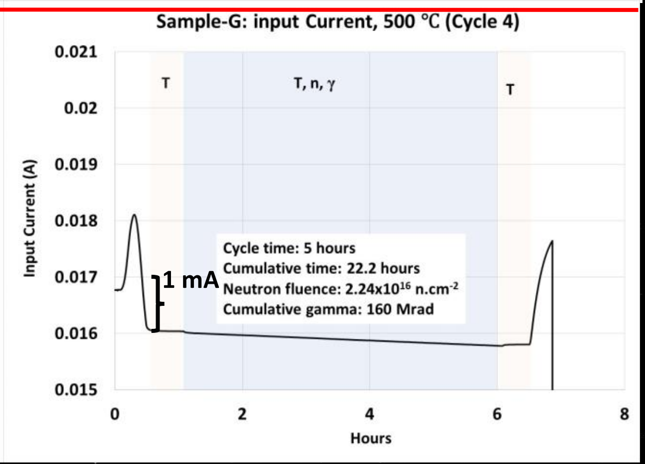








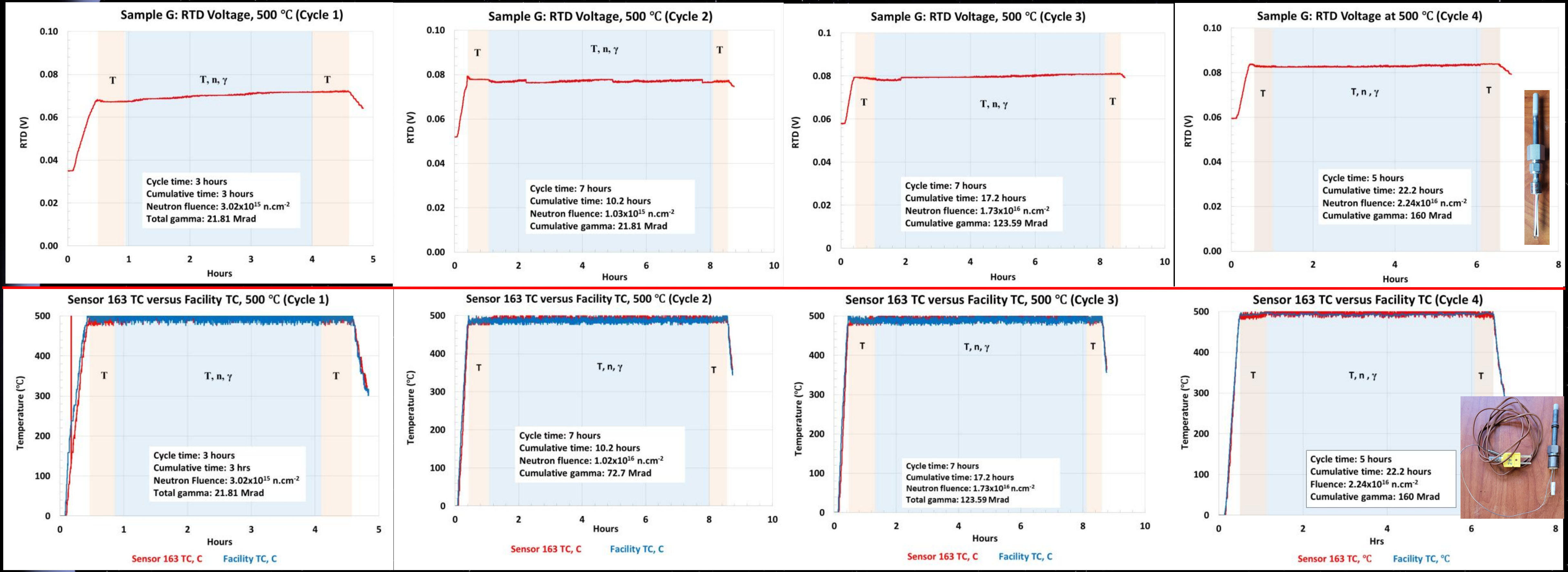




- Parabolic increase and linear decrease.
- At 500 C: <u>Parabolic current increase not observed</u>. *In-situ annealing?*
  - Linear decrease in current slows at 500 C, constant rate.

- **Input current decreased (resistance increase), did not return to pre-irradiation values.**
- **Attributed to carrier removal. Responsible for premature failure of semiconductor electronics.**

On-Chip RTD/Package Embedded Type-K vs Reactor Type-K Thermocouple at 500 ℃



- On-Chip RTD remained stable at steady state range.
  - No apparent γ-induced charging on the RTD.
  - Shifts and some drifts at 500 C
- Package embedded Type-K TC tracked reactor TC very well and showed no drift or shifts

Summary of ZPO and RTD Parameters
(Unshielded sensors state of the art)

				ZPO			RTD			
Samples	Cycles	Total Fluence (10^{16} n.cm^{-2})	Min. Total γ (Mrad)	CRS (%)	RS (%)	Drift (mV)	CRS (%)	RS (%)	Drift (mV)	Current Loss (mA)
A	1	0.11	8	-1.10	-1.10	-28.00	46.34	46.34	Unstable	0.15
	2	0.51	37	-4.95	-3.89	-0.40	4.39	-28.67	-4.00	0.45
	3	1.22	88	-5.70	-0.30	-56.00	6.30	-6.20	0.40	N/A
B	1	0.40	29	-1.19	-1.19	0.00	-5.56	-5.56	1.40	0.25
	2	1.11	80	-3.16	-2.00	-25.00	-8.33	-2.94	2.50	N/A
C	1	0.40	29	0.50	0.50	5.00	<0.01	<0.01	1.00	0.4
	2	1.11	80	0.53	0.03	2.50	<0.01	<0.01	1.00	1.5
	3	1.80	131	0.53	0.00	1.50	<0.01	<0.01	0.50	2.55
	4	2.21	160	N/A	N/A	2.00	N/A	N/A	0*	N/A
G (500 ℃)	1	0.30	21.8	86.32	86.32	<4	17.26	17.26	4.00	0.3
	2	1.03	72.7	125.86	21.23	9.00	16.81	-0.38	1.00	0.6
	3	1.73	123.59	110.07	-6.99	15.00	24.30	6.41	3.00	1
	4	2.24	160	N/A	N/A	5.00	N/A	N/A	1.00	N/A

*From onset of stability

- Combined T, n, γ resulted in very high ZPO/RTD CRS and RS parameters.
- These worse case performance parameters to be used as baseline future development.
- Results identify areas that require improvement, being conscious of radiation hardness:
  - Sensor contact metallization.
  - More robust packaging.
  - Reduce wafer-wafer variations.
  - Integrated shielding concepts.

Conclusion

- Evaluated ZPO and RTD of unshielded State of the Art integrated SiC pressure/temperature sensors under combined neutron/gamma irradiation and temperature up to 500 ^{o}C

- Unheated or heated, in most cases, *ZPO* and RTD voltages trended toward pre-irradiation values.

- Combined High T, n, γ resulted in very high ZPO and RTD CRS and RS.
  - The ZPO and RTD exhibited various degrees of drifts from sample to sample.
  - RTD instability was likely due to γ-induced oxide charging.
  - Phenomenon not observed at 500 ^{o}C.

- Parabolic rise in current seen in unheated samples also not observed at 500 ^{o}C.
  Reduction in current (increased resistance) likely due to carrier removal.
  Known to degrade performance of semiconductor electronics.

- Results are base-line worse case parameters, providing foundational understanding of the performance characteristics of the integrated SiC pressure/temperature transducers to neutron and gamma irradiation.
  - Knowledge gained will help improve sensors' reliability and be viable for FSP and SMR applications.

Caveat: Large sample population required to gain increased statistical confidence

Next Steps

<u>Super-RTE (Awarded)</u>: Conduct *"In-Operando Performance Characterization of On-Chip Integrated SiC Pressure/Temperature Sensors under Irradiation"* to understand radiation effects on piezoresistance (sensitivity).

$$\mathbf{V\,(T,P) = V_{ZPO}(T) + S(T)P}$$

↓

Pressure Sensitivity (Gauge Factor)

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THANK YOU!