



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

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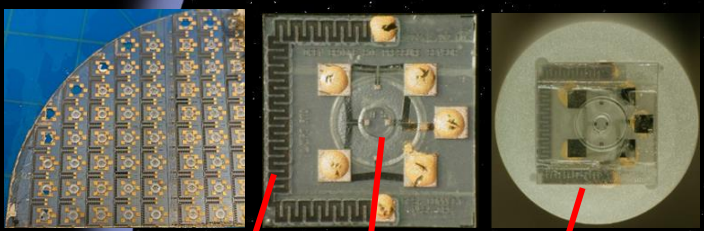
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# Motivation

- 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 ( $\sim 800$  °C) 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



Pt RTD SiC Pressure Sensor



Package-embedded TC



P/T (RTD)

Fully Packaged SiC P/T Transducer  
[www.nasa.gov](http://www.nasa.gov)

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

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.

ZPO/RTD Only (NSUF – RTE)(OSU)

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

This presentation

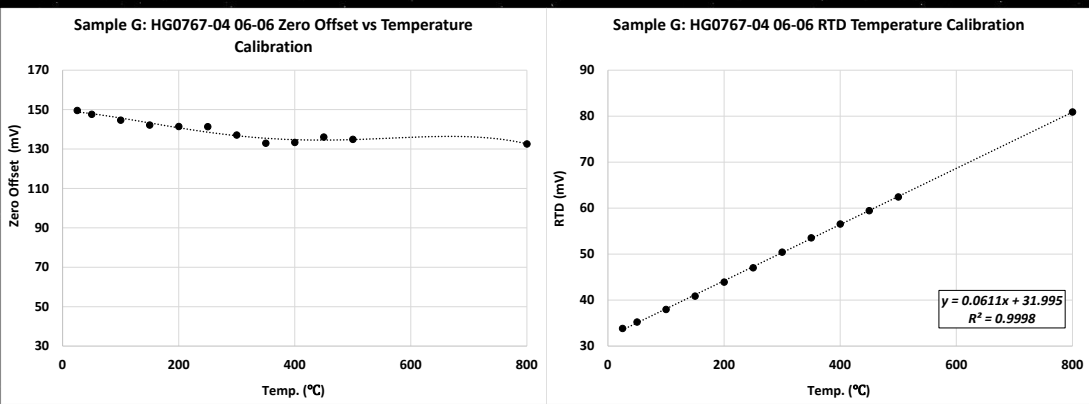
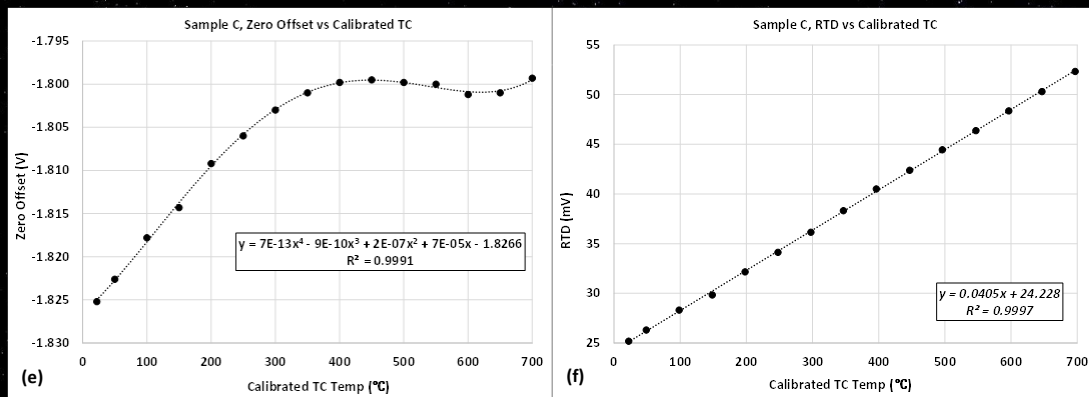
ZPO/RTD and S: P, T, n, γ (Super RTE at MIT)

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

# ZPO and RTD Oven Characterization

## ZPO Characteristics

## RTD Characteristics



Each sensor has its unique characteristics, hence calibrated individually

### Performance Parametrics

CRS=Cumulative Relative Shift across aggregate cycles  
RS=Relative Shift after each cycle

$$CRS = \frac{ZPO(t) - ZPO_{pre-irradiation}}{ZPO_{pre-irradiation}} \times 100 \%$$

$$RS = \frac{ZPO(t) - ZPO_{initial}}{ZPO_{initial}} \times 100 \%$$

**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 parametrics

Sample C  
(T, n, γ)

Sample G  
[T (500 C),  
n, γ]

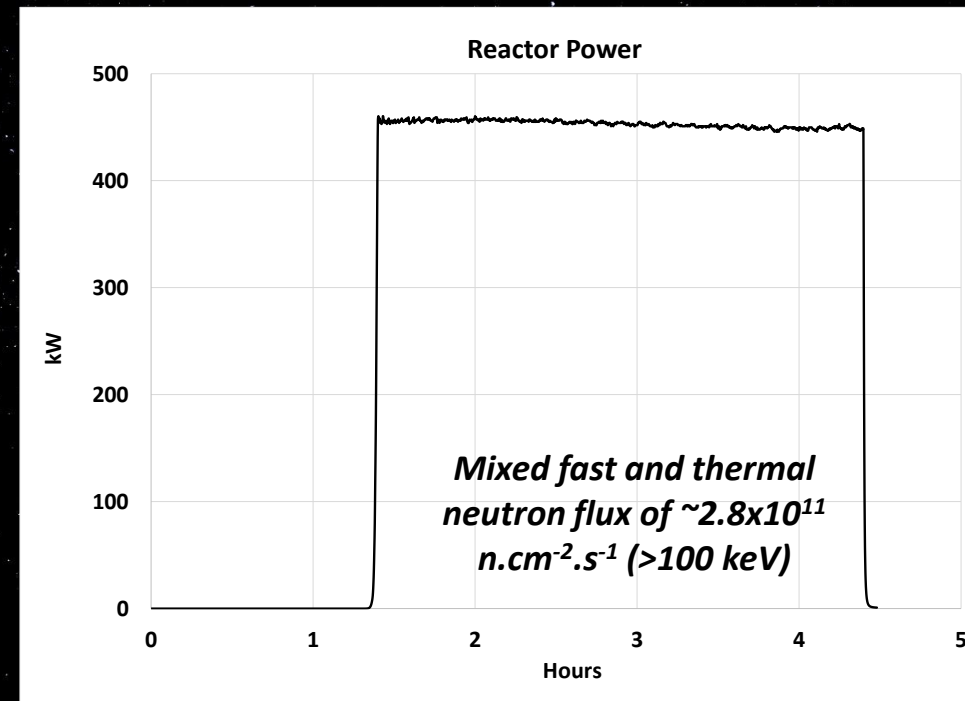
# Test Setup

Sample #	Doping Conc. (cm <sup>-3</sup> )	Total Fluence (n·cm <sup>-2</sup> )	Total <b>Minimum</b> Gamma (Mrad)	Cumulative Time (hrs)
A	10 <sup>19</sup>	~1.22x10 <sup>16</sup>	88	12.1
B	10 <sup>19</sup>	~1.12x10 <sup>16</sup>	80	11
C	10 <sup>19</sup>	~2.22x10 <sup>16</sup>	160	22
G (500 °C)	10 <sup>19</sup>	~2.24x10 <sup>16</sup>	160	22.2

Samples A, B, and D from same wafer



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

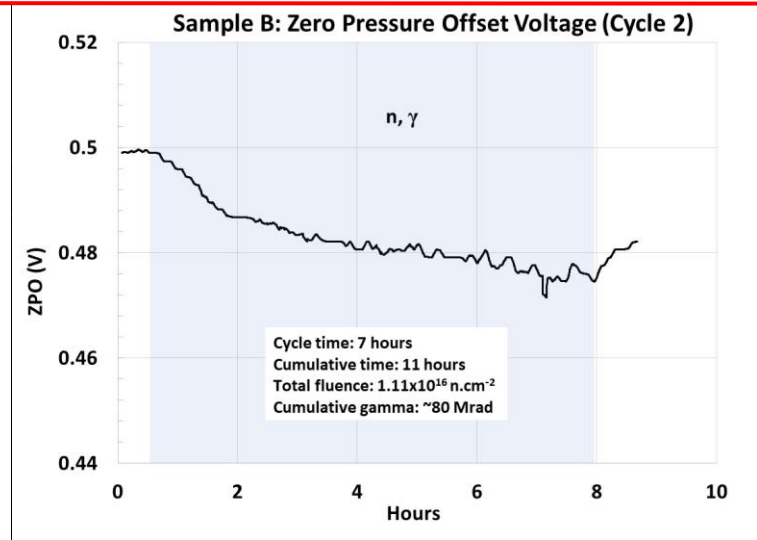
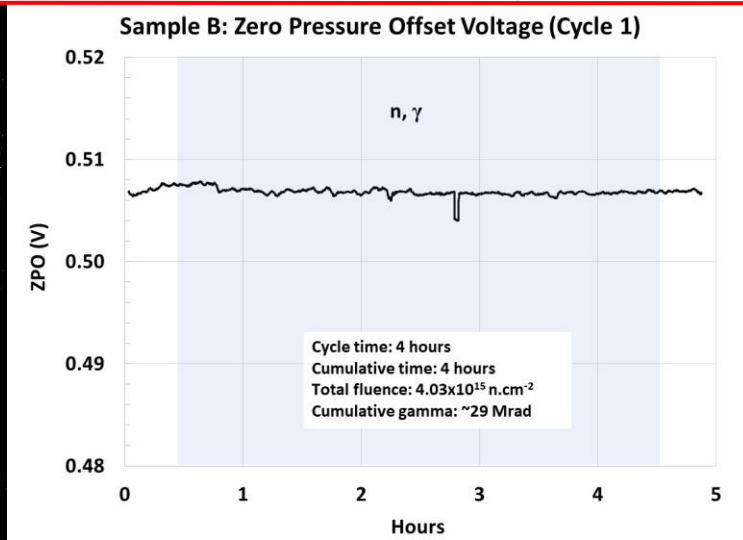
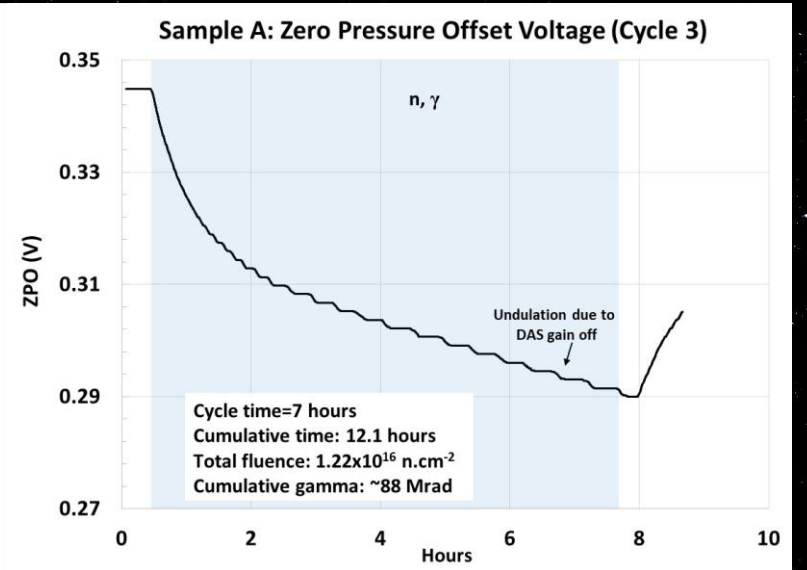
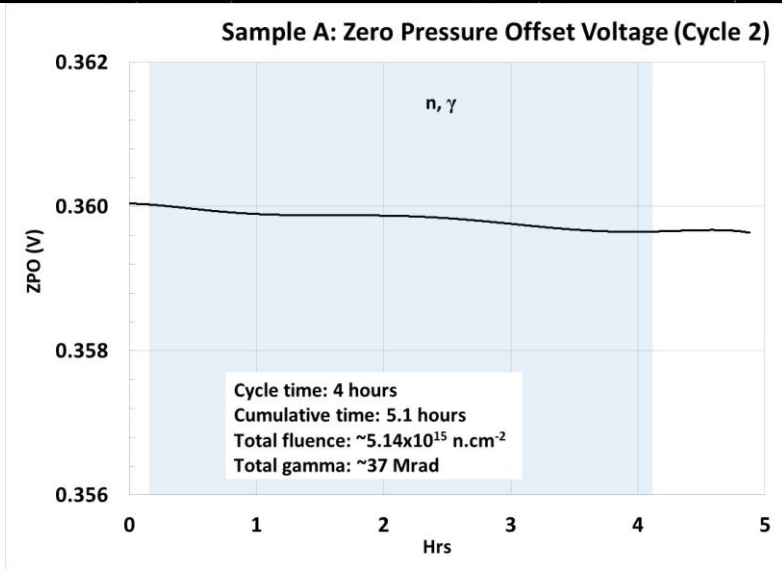
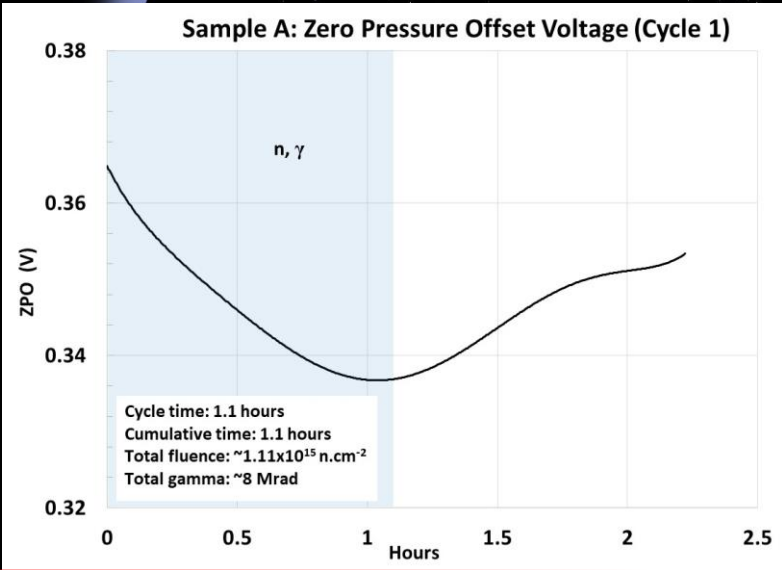


Typical reactor power profile used during irradiation



# Pressure Sensor ZPO Response

(Samples A and B)

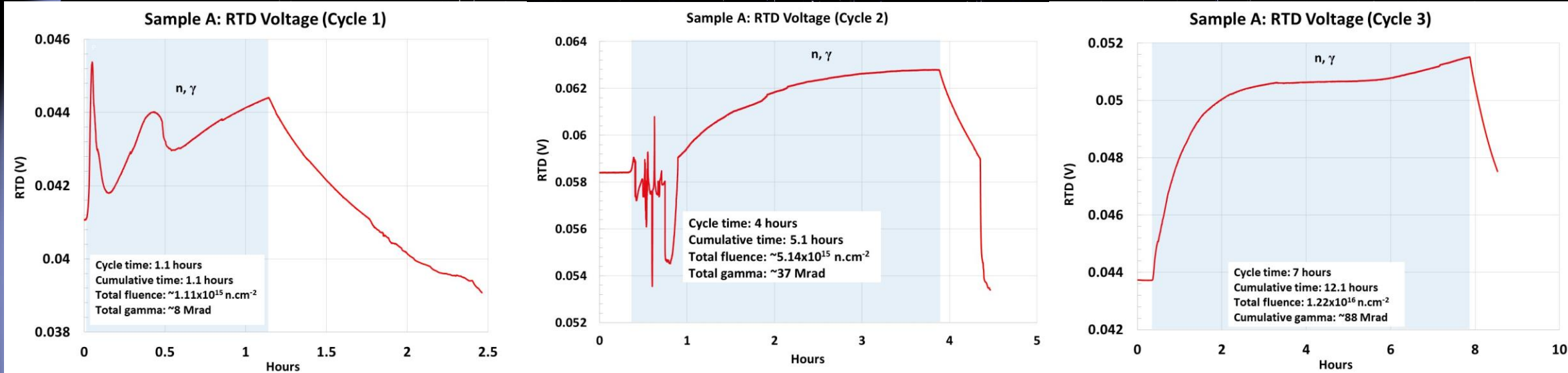


- ZPO trending toward pre-irradiation values.
- Small and large drifts.

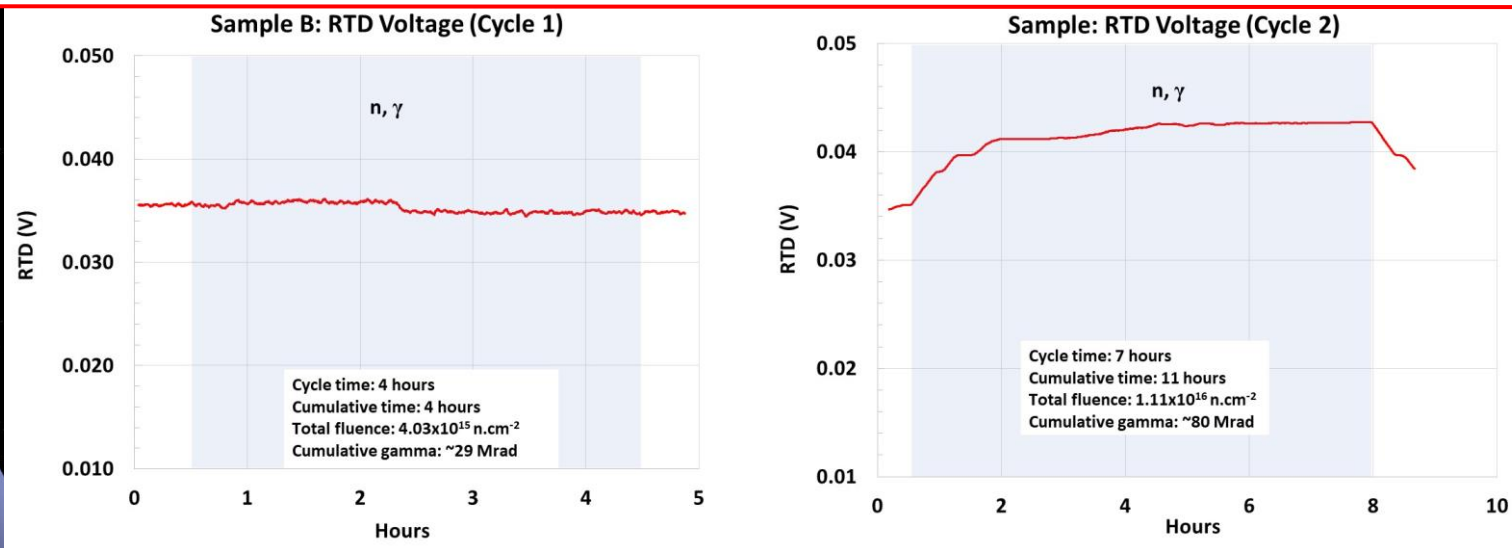
# On-Chip Integrated RTD Response

(Samples A and B)

## Sample-A



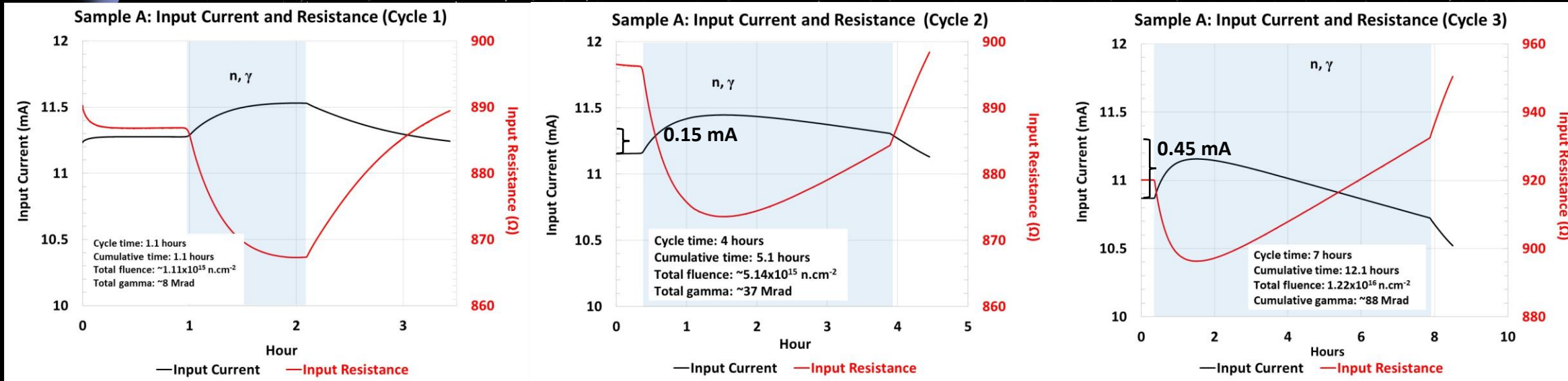
## Sample-B



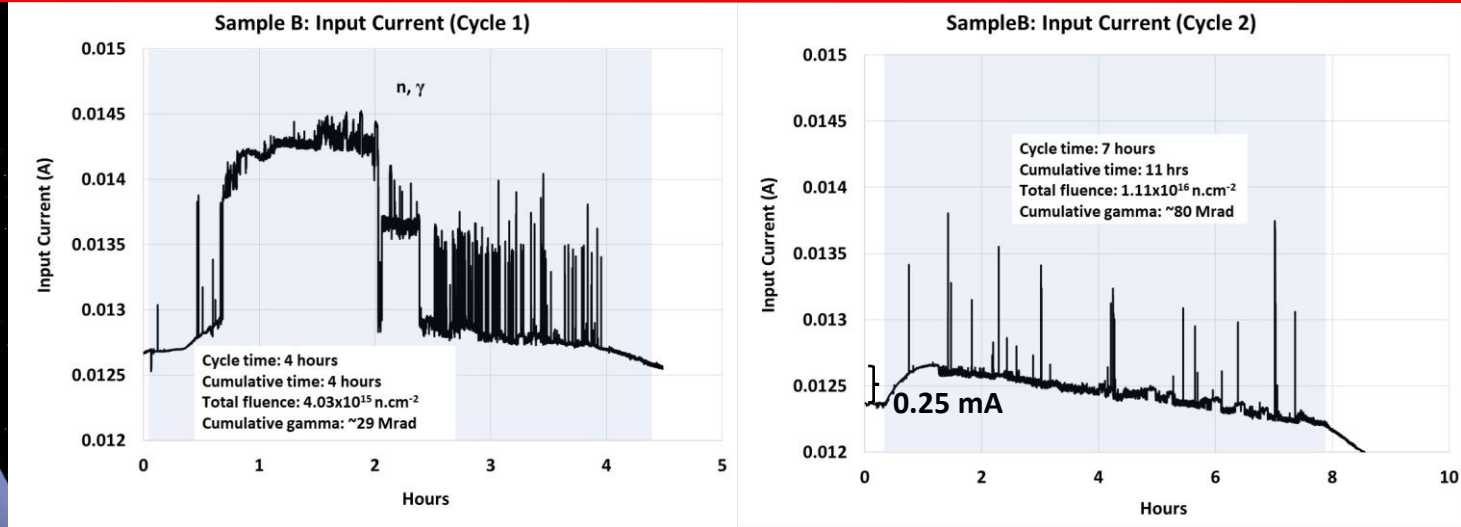
- **Sample A: Breakdown of non-radhard plastic insulation. Replaced on subsequent samples.**
- **Other than Cycle 2 of Sample A, both samples trended toward pre-irradiation values.**
- **Small drifts in B; large drifts in A.**

# Pressure Sensors Input Current Response (Samples A and B)

## Sample-A



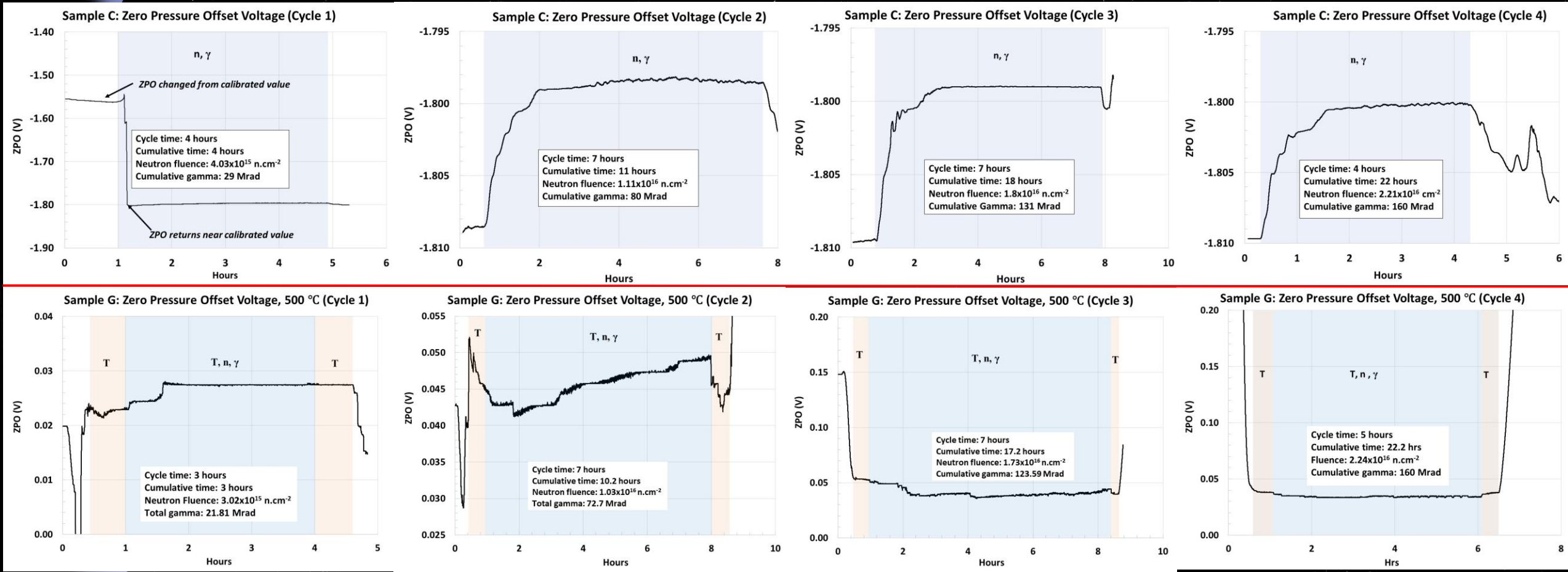
## Sample-B



- 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

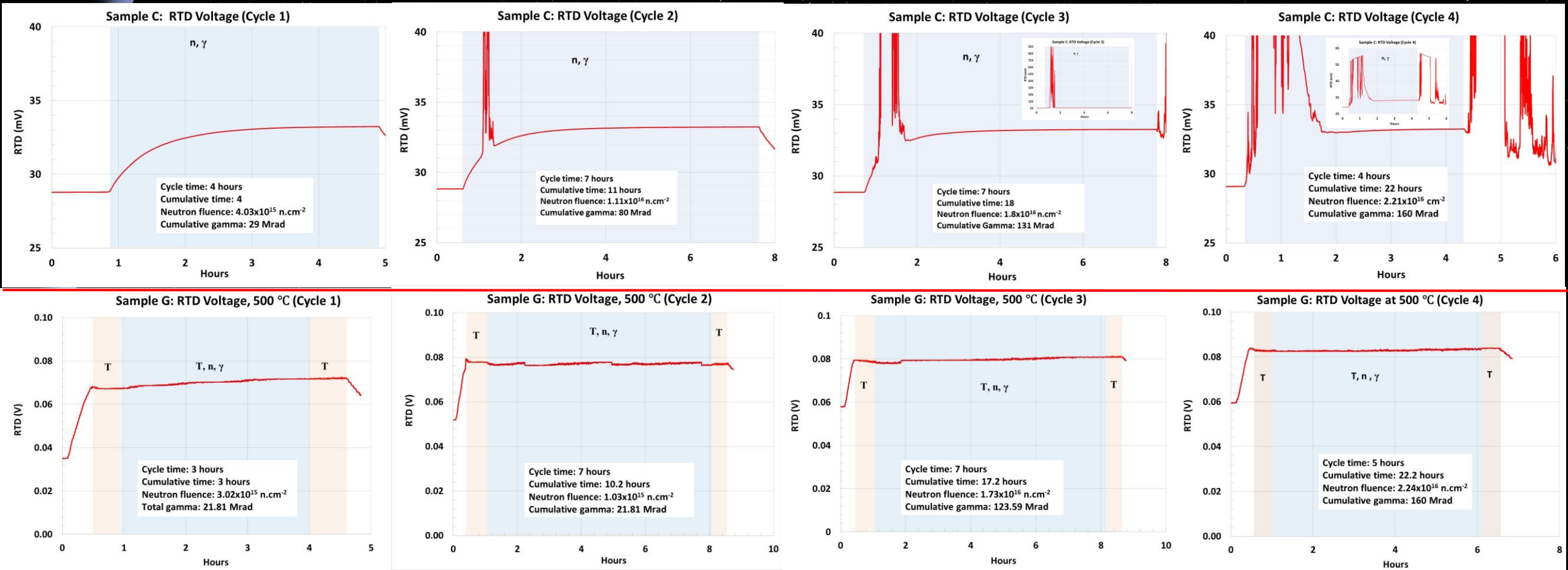
## Comparison: Samples C (unheated) and G (500 °C)



- 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 °C) yet to be understood. Contact metallization suspected.
- Shift in pre-irradiation ZPO values likely due to wiring assembly.

# On-Chip Integrated RTD Response

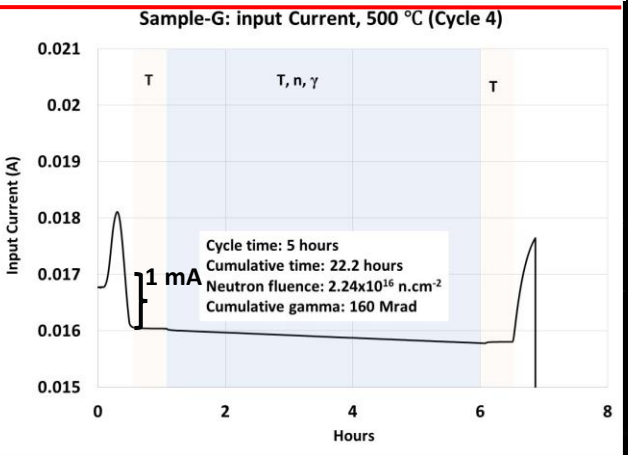
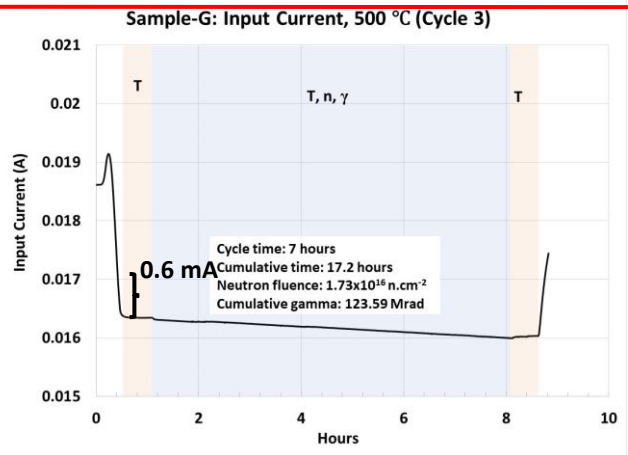
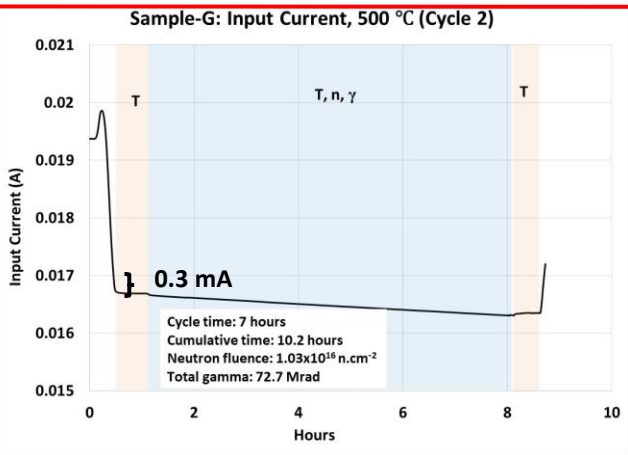
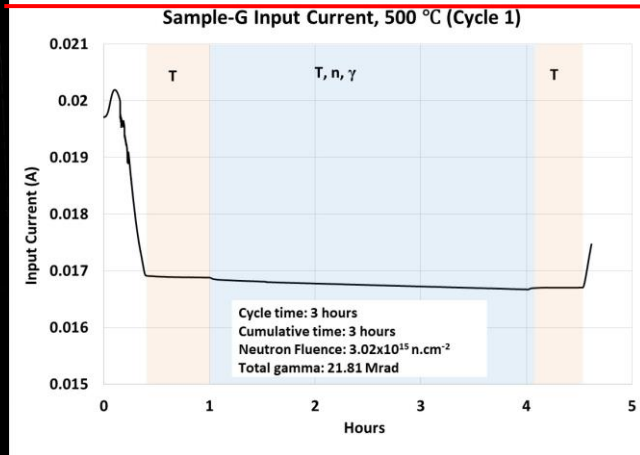
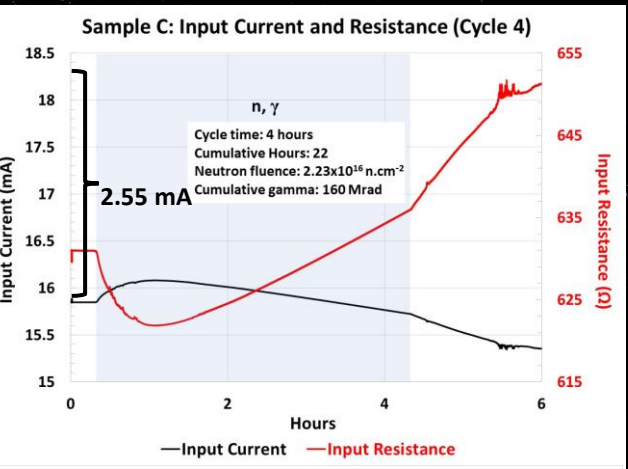
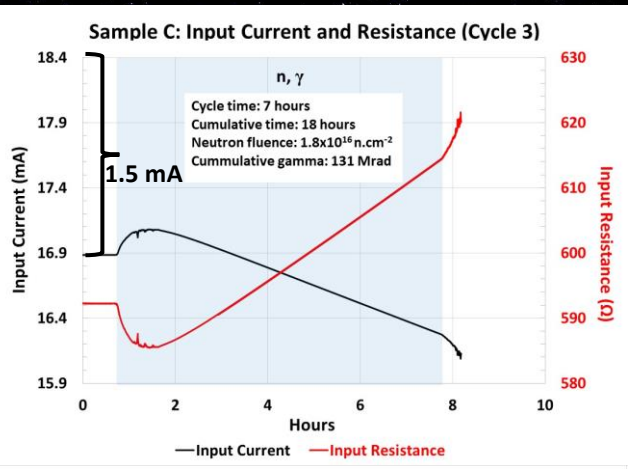
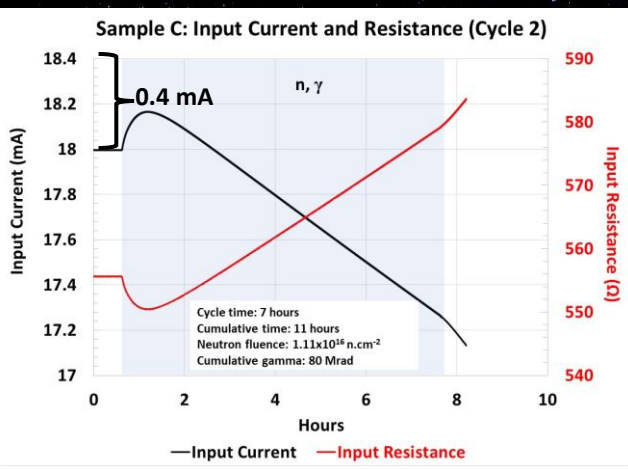
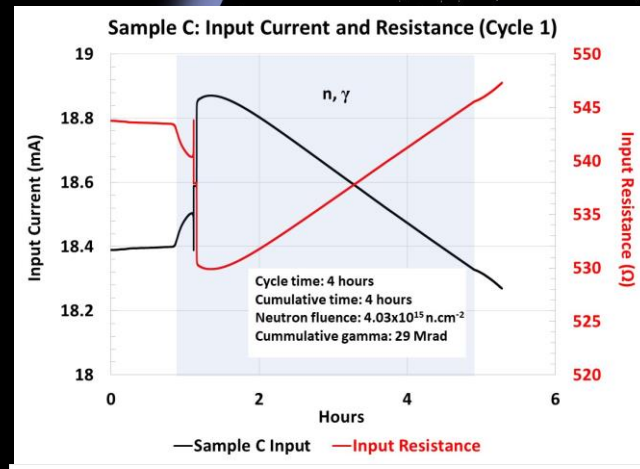
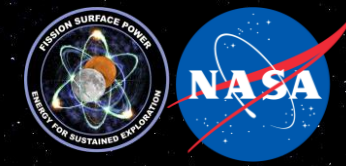
## Comparison: Samples C (unheated) and G (500 °C)



- Sample C: instability before and after irradiation-possibly  $\gamma$ -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

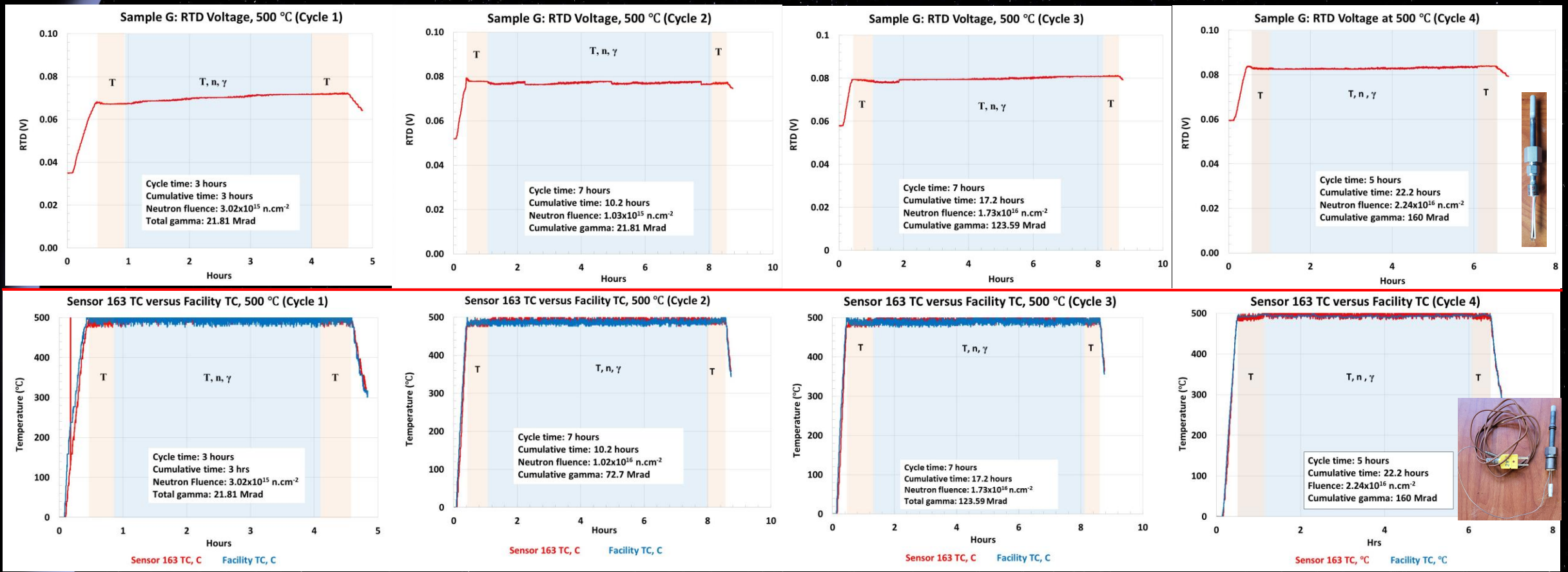
Comparison: Samples C (unheated) and G (500 °C)



- Parabolic increase and linear decrease.
- At 500 C: Parabolic current increase not observed. 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.

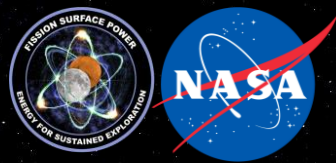
# On-Chip RTD/Package Embedded Type-K vs Reactor Type-K Thermocouple at 500 °C



- On-Chip RTD remained stable at steady state range.
  - No apparent  $\gamma$ -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)



Samples	Cycles	Total Fluence ( $10^{16}$ n.cm <sup>-2</sup> )	Min. Total $\gamma$ (Mrad)	ZPO			RTD			Current Loss (mA)
				CRS (%)	RS (%)	Drift (mV)	CRS (%)	RS (%)	Drift (mV)	
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 °C)	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  $T$ ,  $n$ ,  $\gamma$  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 °C
- Unheated or heated, in most cases, ZPO and RTD voltages trended toward pre-irradiation values.
- Combined High  $T$ ,  $n$ ,  $\gamma$  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  $\gamma$ -induced oxide charging.
  - Phenomenon not observed at 500 °C.
- Parabolic rise in current seen in unheated samples also not observed at 500 °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.

# Next Steps

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

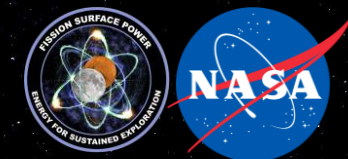
$$V(T, P) = V_{ZPO}(T) + S(T)P$$



**Pressure Sensitivity (Gauge Factor)**



# Acknowledgement



**Technical Staff of the GRC SiC Microfabrication Lab.  
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THANK YOU!