Neutron Irradiation of Materials

BJORN BURKLE, ISAAC FUGATE*, ULRICH HEINTZ, NICK HINTON, SOUMYA GHOSH*, MEENAKSHI NARAIN, ERIC SPENCER, JUSTIN VOELKER

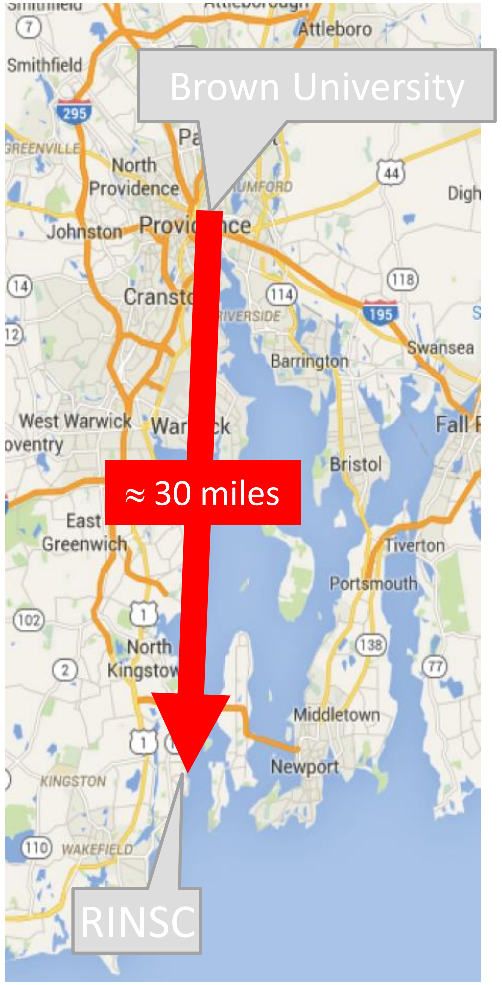
*former members

Neutron Irradiation

- Test sensors will undergo neutron irradiation to test radiation hardness of materials
- There will be two types of irradiation tests, neutron irradiation and proton irradiation
- Neutron irradiation will happen at the Rhode Island Nuclear Science Center (RINSC) located near Brown

Rhode Island Nuclear Science Center

- Thermal neutron reactor located ≈30 miles from Brown
- Two different delivery methods
  - Beam port
    - Samples placed in beam port before ramp up and removed after ramp down
    - Two 6-inch diameter ports and one 8-inch diameter port
      - So far, the 8-inch diameter beam port and one of the 6-inch beam port fluences has been measured, measurements of second beam port is currently underway
  - Pneumatic Rabbit System
    - Samples are delivered and removed from reactor when it is at full power
      - No fluence uncertainty contribution due to ramp up and ramp down of reactor
    - Only samples 35 mm by 90 mm can fit in rabbit system carrier



Beam Port Fluence

- Beam port fluence has been measured using two methods
- **Silicon Diodes**
  - D0 diodes were irradiated in reactor
  - The increase in leakage current of the fully depleted diode is proportional to the 1-MeV equivalent fluence the diode was exposed to.
- **Spectrum Unfolding Via Foil Activation**
  - Foils composed of different pure elements are irradiated in reactor
  - Activity is measured via gamma spectroscopy
  - This method gives us the full spectrum of neutron energies in units of n/MeV/cm^2/s
  - Silicon damage function can be used to obtain a 1 MeV equivalent flux
  - MIDGRAD algorithm is used to find a flux spectrum which minimizes

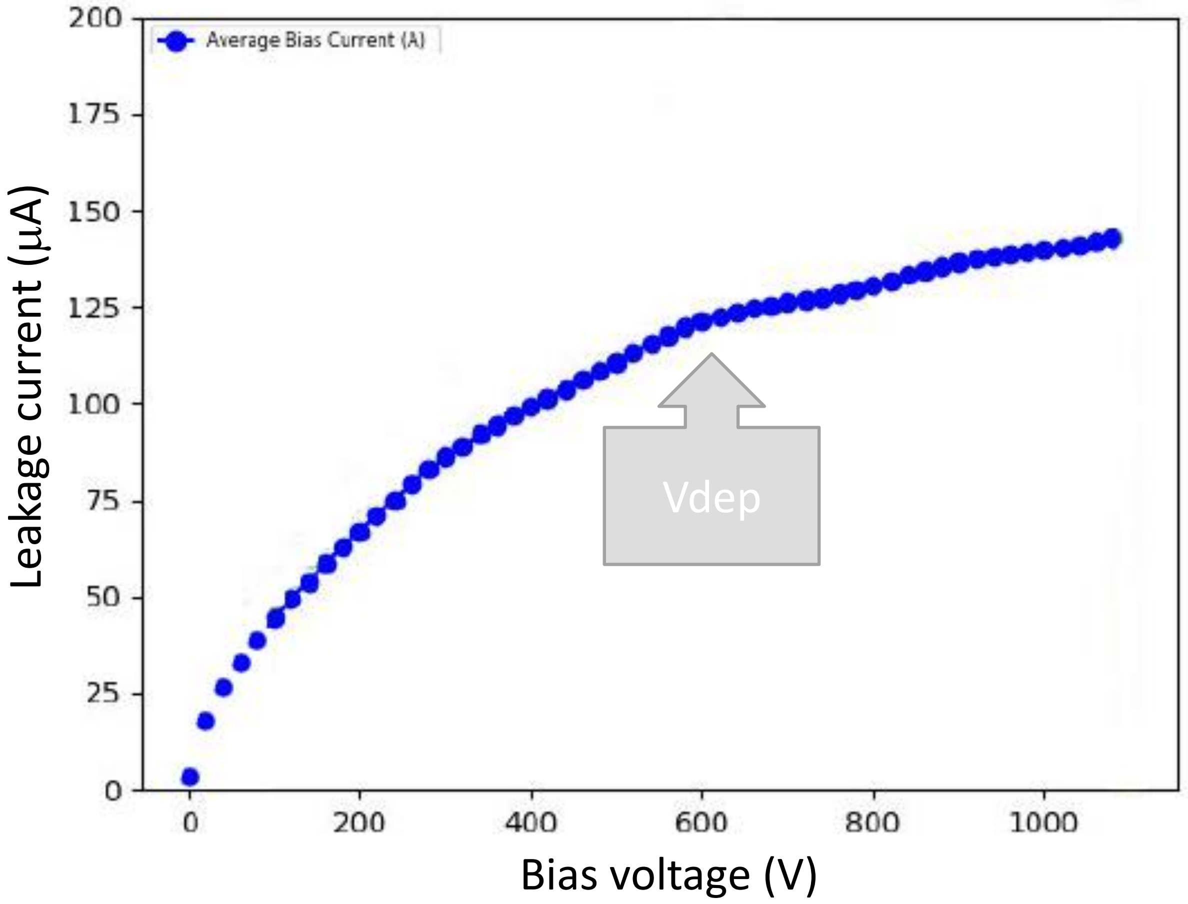
$$\chi^2 = \sum_{\text{foils}} \frac{(A^\infty_{\text{meas}} - A^\infty_{\text{calc}})^2}{(\Delta A^\infty_{\text{meas}})^2}$$

    - A^∞_{meas}- Maximum activity which element can reach from the reactor, obtained from post irradiation activity measurement measurements
    - A^∞_{calc} - Maximum activity which element can reach from the reactor, obtained by calculating the expected activity of the foil based on the elements known activation cross section and the assumed reactor flux spectrum

Diode Based Flux Measurements

- Fluence measurements:
  - 6 – inch beam port:
    - 1 MeV equivalent flux of 2.2E11 n/cm^2/s
    - Only one diode measured
    - Not irradiated with the foils used for other flux measurement method
  - 8 – inch beam port:
    - Diodes were irradiated along with foils

Diode	Vdep	Ileak	Flux
CO16	690 V	0.73 mA	5.7×10^{11} n/cm^2/s
CO17	660 V	0.73 mA	5.7×10^{11} n/cm^2/s
CO18	660 V	0.77 mA	6.0×10^{11} n/cm^2/s
CO19	660 V	0.79 mA	6.1×10^{11} n/cm^2/s
Average			5.9×10^{11} n/cm^2/s



Foil Activation

- Elements which were irradiated with and without Cd coverings:
  - 6 inch beam port – Al, Au, Cu, Fe*, In*, Ni, Sc**, Ti, V, Zr
  - 8 inch beam port – Al, Cu, Fe*, Zr
    - For Fe we looked at the activation of multiple isotopes
    - For indium we only measured the sample which was covered in cadmium
    - Sc became too activated to measure
- Spectrum is modeled using the following form:
  - Maxwellian energy distribution for thermal spectrum:

$$\varphi(E) \propto \sqrt{\frac{E}{(kT)^3}}\, e^{-E/_{kT}}$$

    - Where:
      - *k* = Boltzman's Constant
      - *T* = temperature of thermal neutrons
        - approximated as the temperature of the water the core is submerged in
  - $^1/_E$ distribution for intermediate neutrons
  - Watt Distribution for fission neutrons

$$\varphi(E) \propto \sinh\left(\sqrt{2.29E}\right) e^{-E/_{0.965}}$$

  - For neutrons with *E* > 12 MeV added an exponentially decaying tail to Watt Distribution.
    - This was done to better fit the Zr activity measurements
    - Recent testing has shown that it has a negligible effect on the 1 MeV equivalent flux, will drop this in future measurements

Comparison of foil activities

Isotope	Threshold	6" data	8" data
Zr	>12 MeV	4.99E-17	8.43E-17
Zr cd		4.97E-17	8.14E-17
V	>6 MeV	4.89E-18	
V cd		4.20E-18	
Al	>5 MeV	1.81E-16	4.36E-16
Al cd		1.82E-16	3.94E-16
Ti	>4.5 MeV	5.68E-17	
Ti cd		5.91E-17	
Fe56	>4 MeV	3.18E-16	
Fe56 cd		2.25E-16	
Fe54	>0.8 MeV	2.22E-14	3.04E-14
Fe54 cd		1.47E-14	3.40E-14
Ni	>0.5 MeV	1.85E-14	
Ni cd		1.91E-14	
Fe58	thermal	3.87E-12	6.29E-12
Fe58 cd		4.80E-14	3.26E-13
Cu	thermal	1.04E-11	3.70E-11
Cu cd		1.37E-13	1.46E-12
Au	thermal	2.95E-10	
Au cd		1.71E-11	
In cd	thermal	6.64E-12	

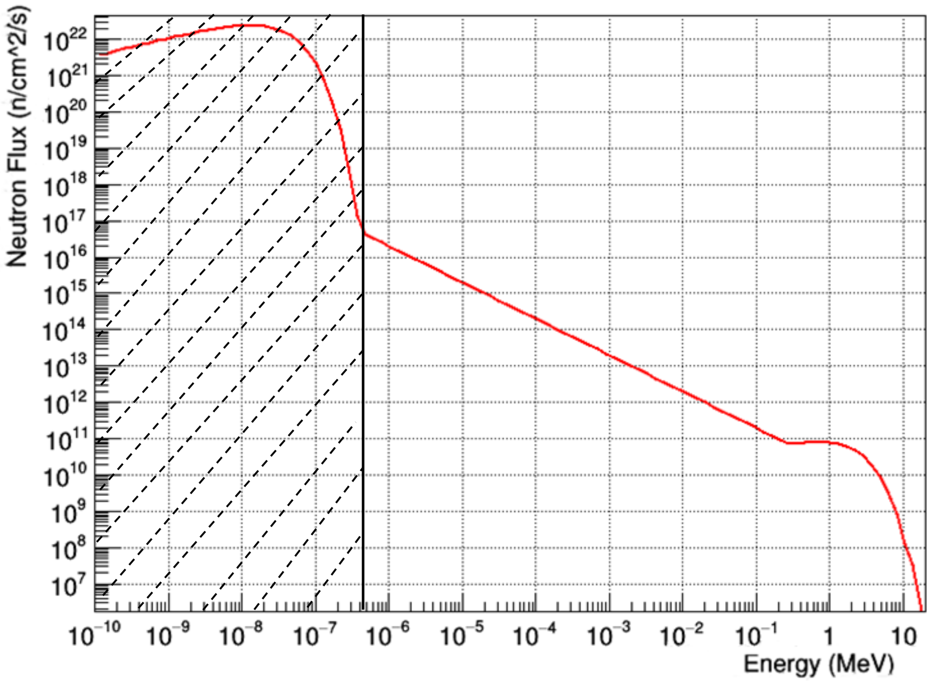
Multiple foils of the same element are consistent to ≈10% once outliers are removed

Foils sensitive to high energy neutrons show about twice the activity for the 8” beam port

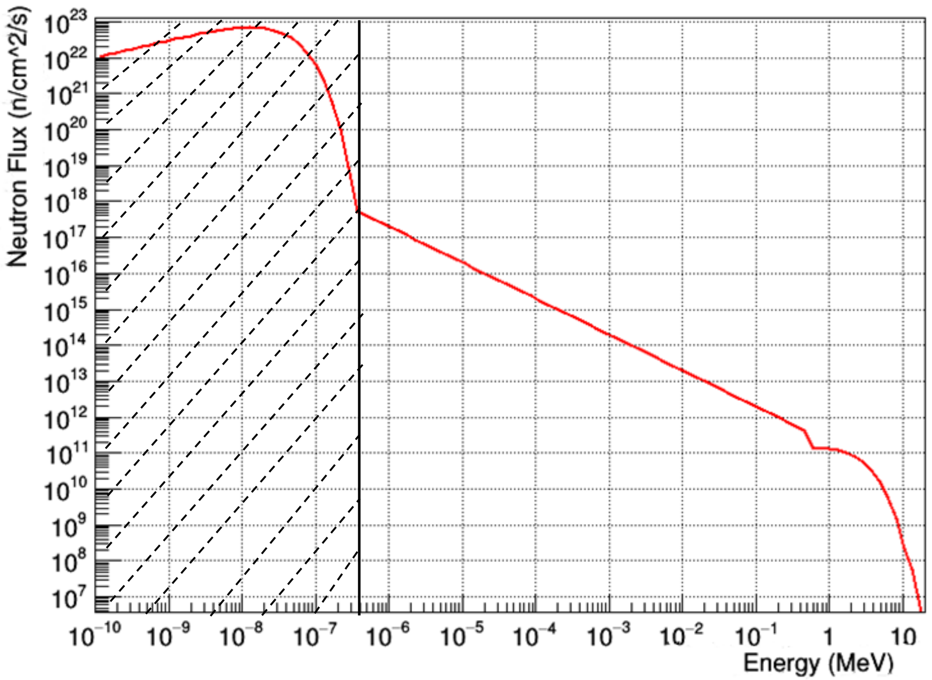
Foils sensitive to thermal neutrons show a larger increase in activity for the 8” beam port

Foil Activation

6 inch beam port if we exclude the thermal region:
1 MeV equiv flux of 2.4E11 n/cm^2/s



8 inch beam port If we exclude the thermal region:
1 MeV equiv flux of 5.6E11 n/cm^2/s



Very large uncertainty in thermal region due to the fit's sensitivity to our choice of foils irradiated. When excluding the thermal region, 1 MeV equivalence seen in the 6-inch beam port is similar to what we measured after integrating over the entire spectrum after fitting to all of the irradiated foils.

Reactor 1 MeV Equivalent Flux

6 – inch port

- Diode measurements:
  - 2.3E11 n/cm^2/s
- Foil measurements (thermal spectrum excluded):
  - 2.4E11 n/cm^2/s
- A second measurement is underway to measure the flux of the second 6 – inch beam port

8 – inch port

- Diode measurements:
  - 5.9E11 ± 2E10 n/cm^2/s
- Foil measurements (thermal spectrum excluded):
  - 5.6E11 n/cm^2/s
- A second measurement of the 8 – inch beam port is being planned to verify our hypothesis about the over estimation of the thermal neutron spectrum

Irradiation Times

Desired Fluence	Approximate Irradiation Time	
	6 – inch port	8 – inch port
10^{14} n/cm^2	7 minutes	3 mins
10^{15} n/cm^2	1 hours 10 mins	$^1/_2$ hour
10^{16} n/cm^2	12 hours	5 hours

Summary

- Sensors will be irradiated at the RINSC reactor near Brown
- Reactor flux at the different irradiation delivery sites have been measured using two different methods
  - 6 – inch beam port measurements agree within <5%
  - 8 – inch beam port measurements agree within RMS of the diode measurements
    - Agreement in both beam ports is seen after we exclude the thermal spectrum of our fit
    - Data suggests that the thermal spectrum was measured improperly due to our selection of materials irradiated
- Two more sets of measurements are underway or being planned
  - Measure the spectrum of the second 6 – inch beam port
  - Remeasure the 8 – inch beam port using a new selection of foils to verify our hypothesis about the thermal spectrum measurement