



THE OHIO STATE UNIVERSITY

Neutron Flux Detector in Nuclear Reactors

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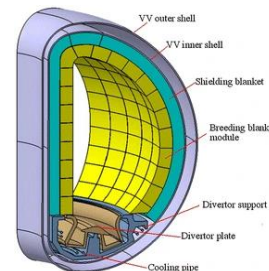
Director, Oklo Nuclear Reactor Laboratory

The Ohio State University

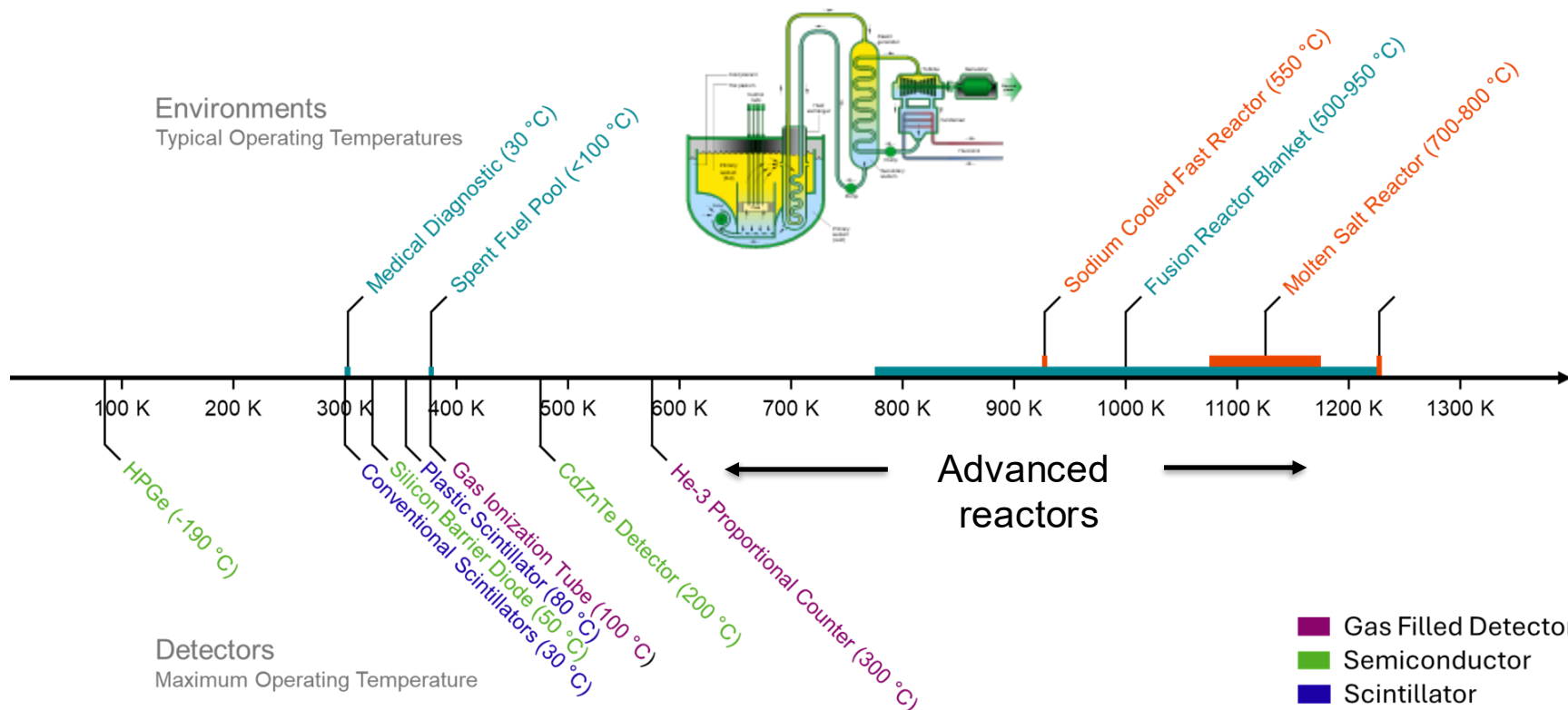
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- Nuclear energy: fission and fusion systems (high temperature & high radiation field)
- Non-proliferation, Nuclear Fuel Cycles (at or above nature background level)

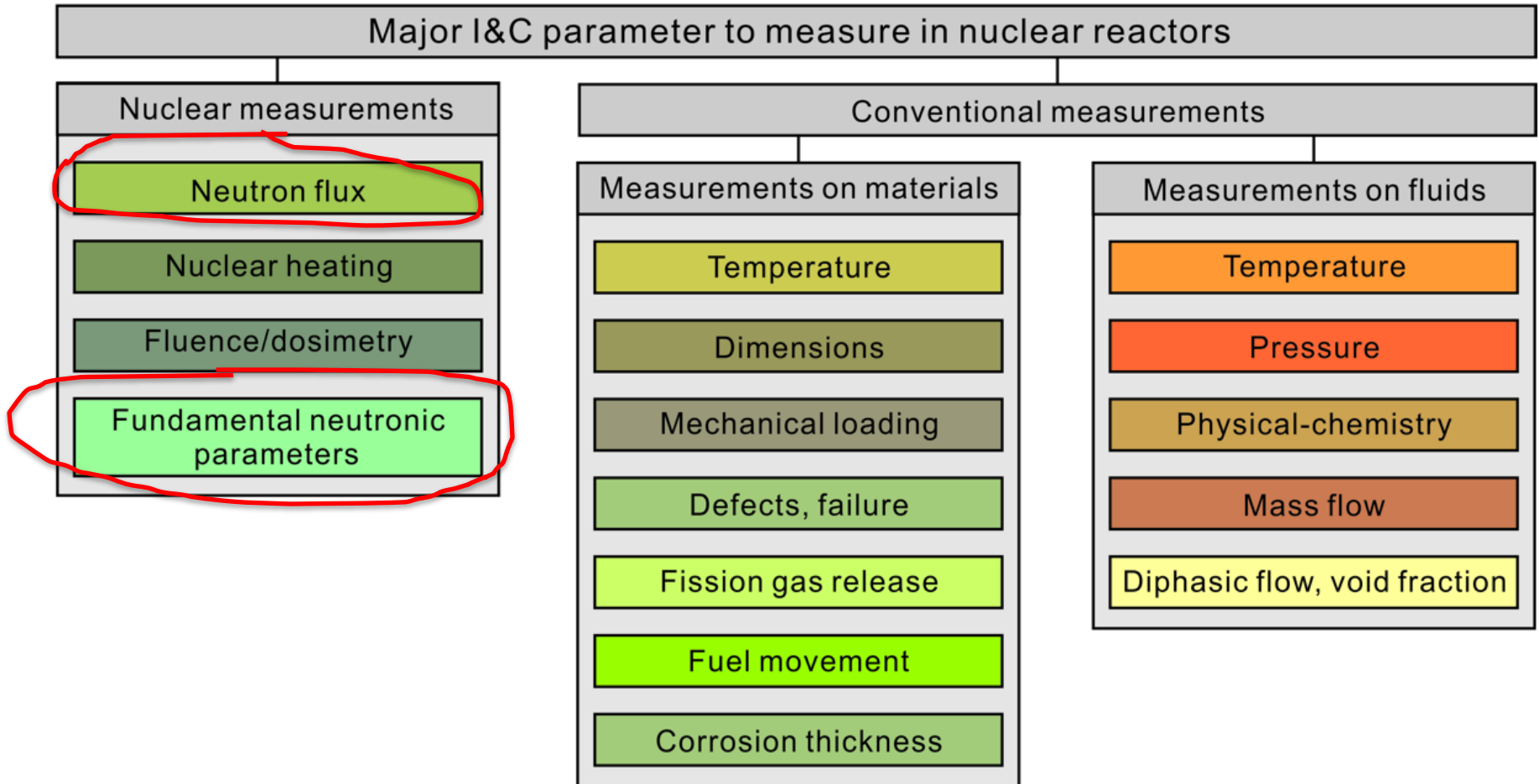


- In-core neutron flux
- Fusion Diagnostics
- Actinides detection





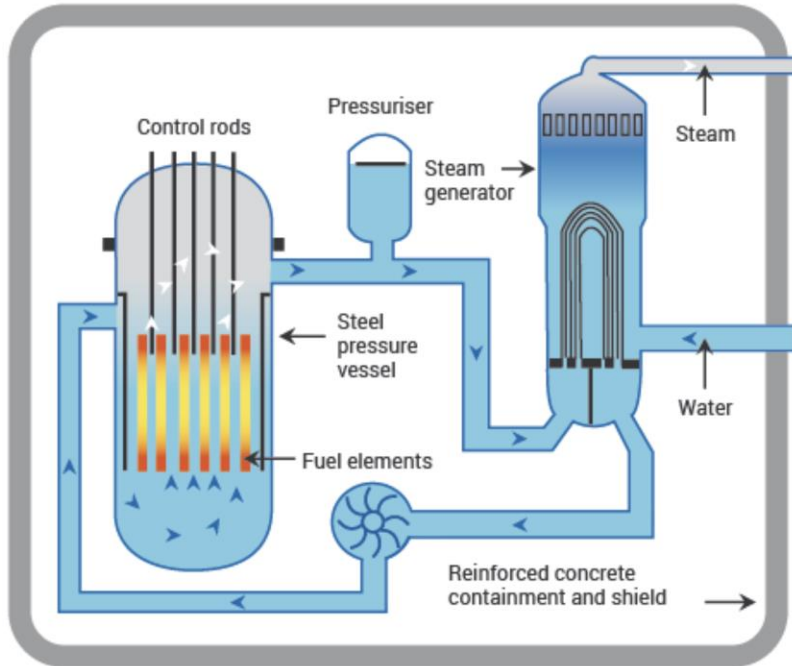
Things to Care





Light Water Reactors

A pressurized water reactor (PWR)



307/440 (73%)

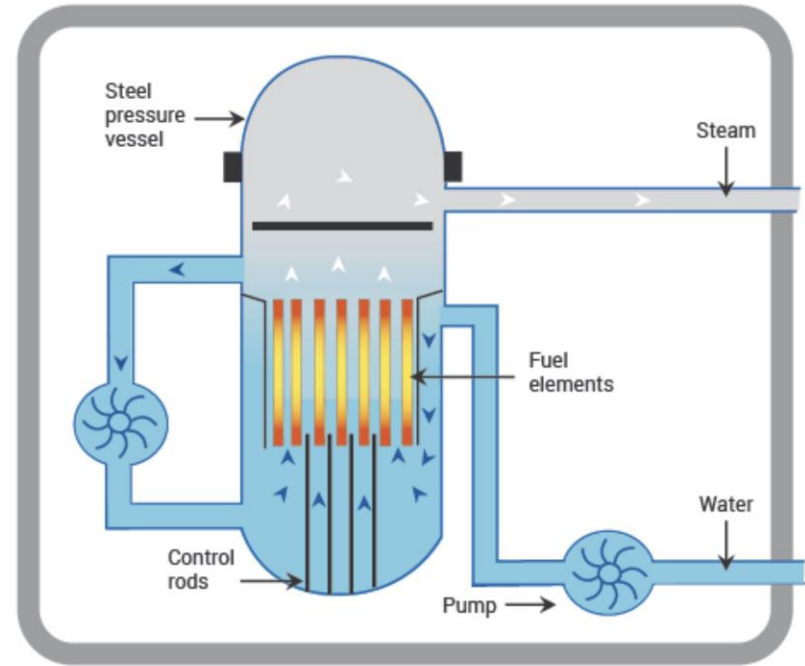
Pressure: 15.5 MPa

Average core temperature: $\sim 305^\circ\text{C}$

Gamma dose rate: 100–1000 Mrad/h

Neutron flux: $\sim 5 \times 10^{13}$ nv

A boiling water reactor (BWR)



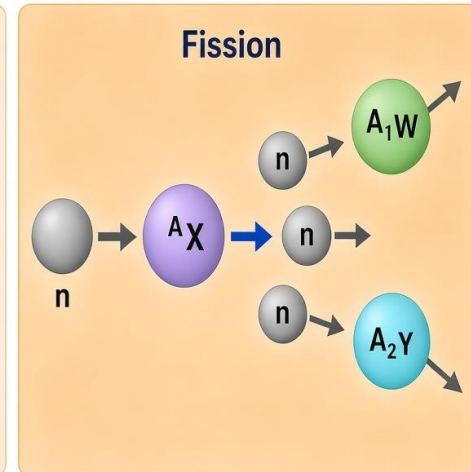
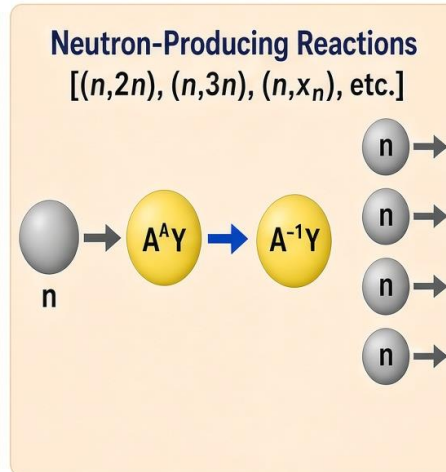
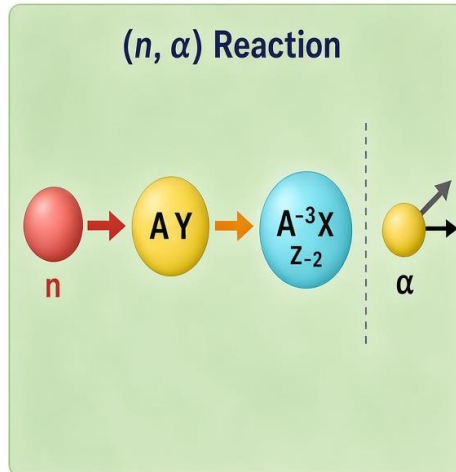
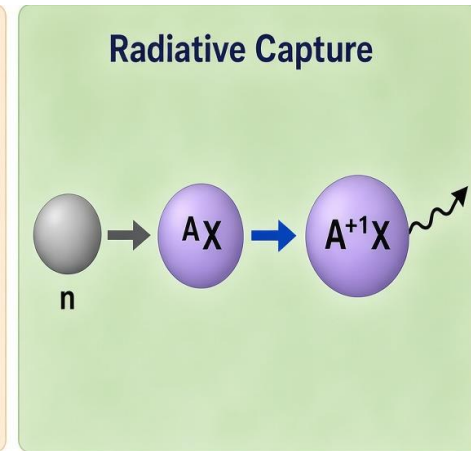
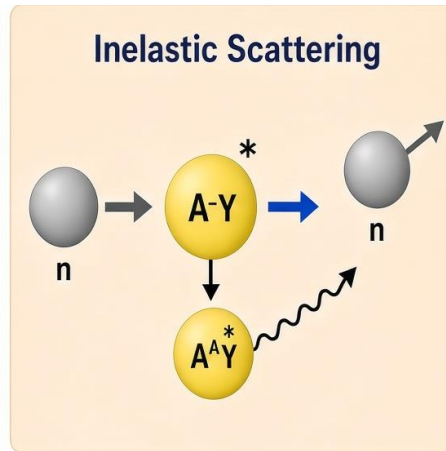
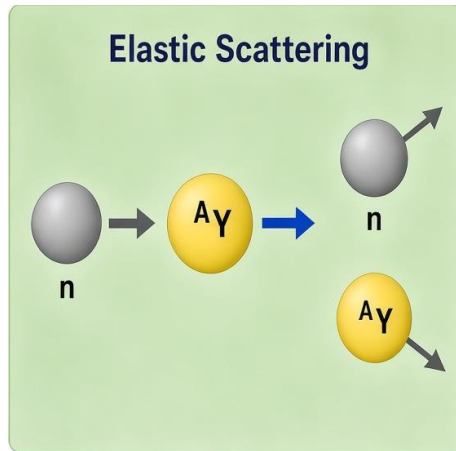
94/440 (21%)

Pressure: 7.1 MPa

Average core temperature: $\sim 286^\circ\text{C}$

Gamma dose rate: ~ 100 Mrad/h

Neutron flux: $\sim 3\text{--}5 \times 10^{13}$ nv



Thermal neutron:
 $E = 0.025 \text{ eV}$
 $V = 2200 \text{ m/s}$

Fast neutron:
 $E = 1 \text{ MeV}$
 $V = 1.38 \times 10^7 \text{ m/s}$



Metal and gas remain the primary detector medium used for in-core neutron flux monitoring today.

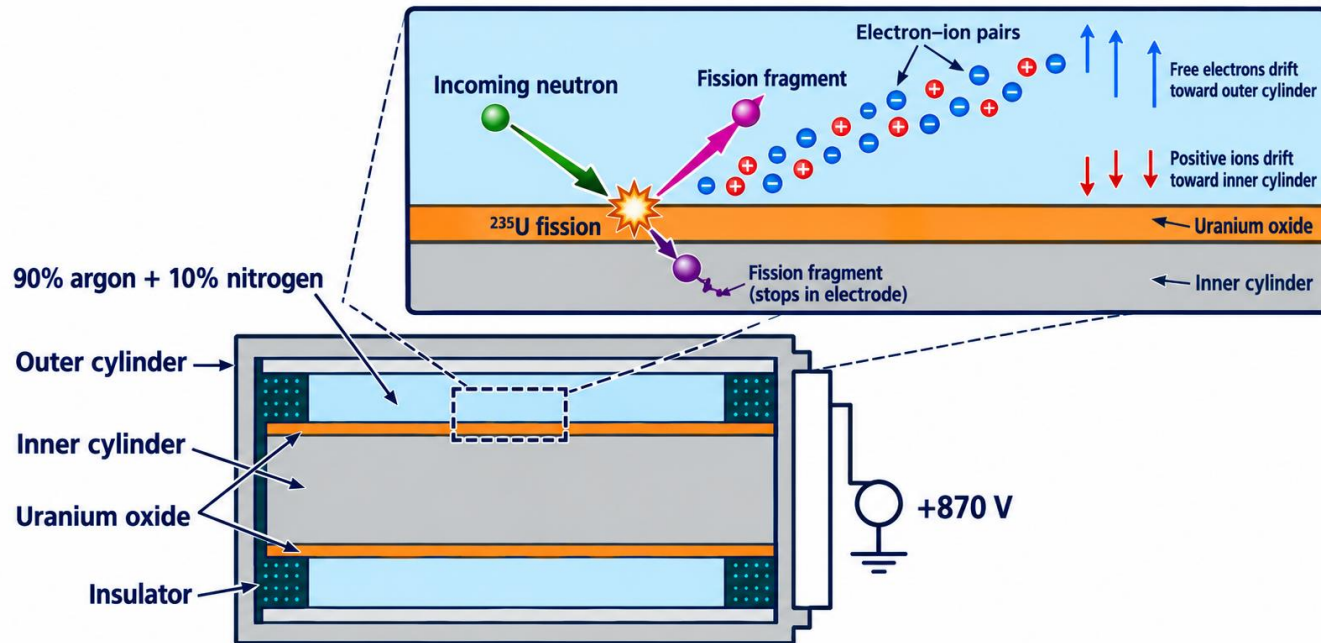
The COTS technologies:

- Fission Chambers
- Ionization Chambers
- Proportional Counters
- Self-Powered Neutron Detectors

Emerging technologies (including for fuel cycle)

- Radiation tolerate fiber optics sensor
- Micro-Pocket Fission Detectors
- Glass scintillator
- Boron neutron straw
- Silicon carbide, Diamond

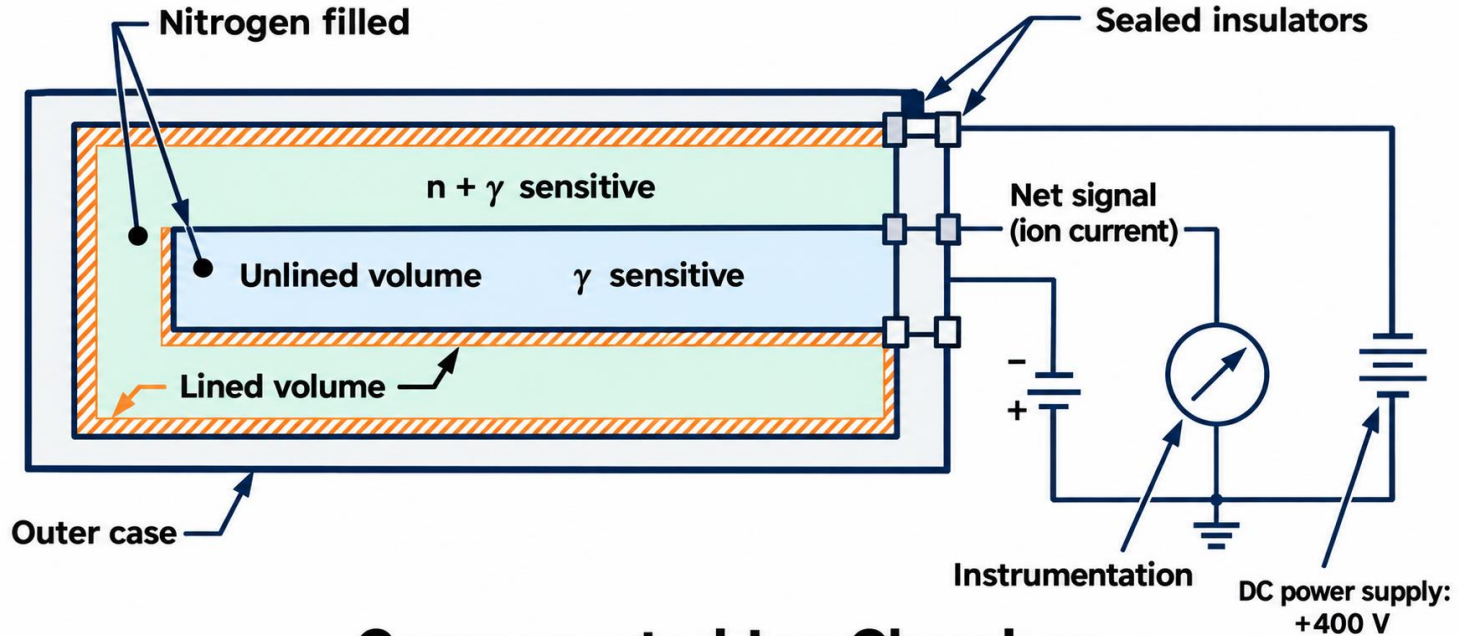
Fission Chamber: Neutron Detection



Neutron capture → fission fragments → gas ionization → electrical signal

Adapted from Knoll book, AI is used for image enhancement

- Operated in one of three modes:
 - Pulse: Monitors the individual reactions event by event
 - Current: Reads the average current from the continuous reactions
 - Mean Square Voltage: Tracks the fluctuations in the signal



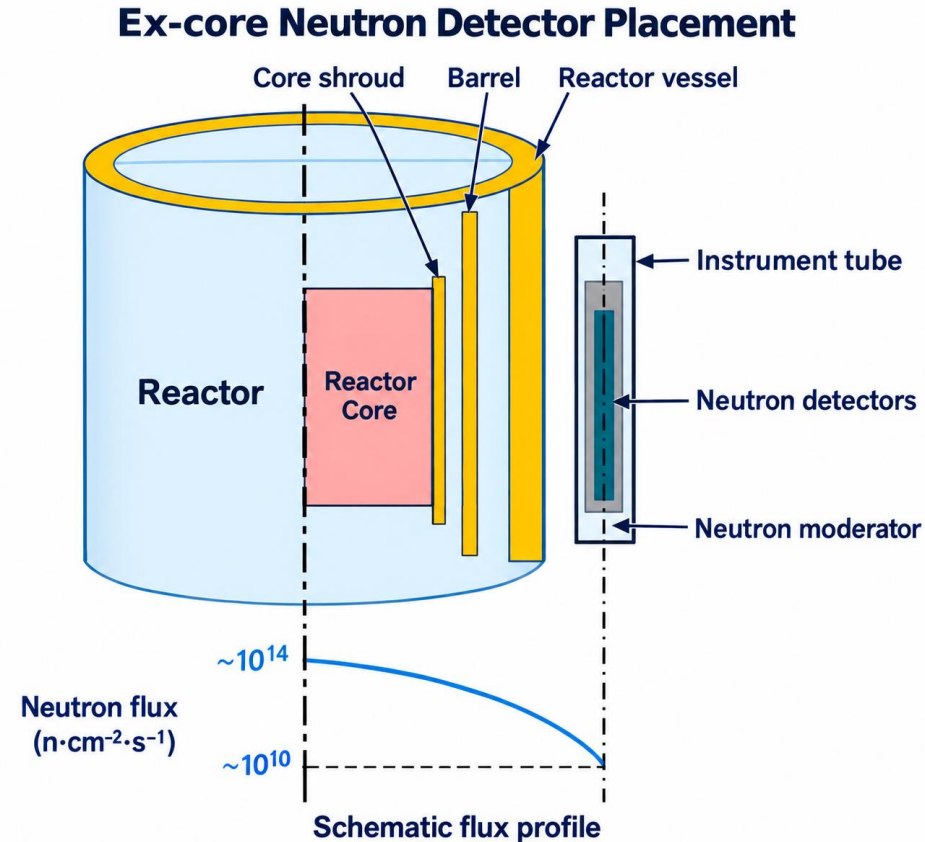
Compensated Ion Chamber

Adapted from Knoll book, AI is used for image enhancement

- CIC is used to suppress gamma contributions so that the output represents neutron flux better.
- Boron-lined region: responds to neutrons and gamma rays.
- Unlined region: responds primarily to gamma rays.



- A BF_3 detector is a **gas-filled proportional counter** for neutron detection
- It contains BF_3 gas, where boron-10 converts thermal neutron to charged particles
- Used as range detectors (very low flux) where one needs high sensitivity to thermal neutrons.
- Ex-core (outside the reactor core) instrumentation in power plants to monitor neutron flux safely.





Source Range Neutron Monitor

Inputs	Ratings
AC Input Power	230 or 120 VAC, Single Phase, $\pm 10\%$, 50/60 Hz, <150 VA
OR	
DC Input Power	125 VDC, $\pm 10\%$, < 150 Watts
Preamplifier Input Impedance	50 Ω typical, other values available upon request
Detector Input Connectors	SHV typical, other input connection types upon request
<i>Note 1: Post-accident monitoring (PAM) functionality requires US NRC RG 1.97 qualified detector.</i>	



<https://paragones.com/corevision-neutron-flux-monitoring-system/>

NEMS Detectors & Cables — Ex-Core

Qualified to IEC/IEEE 323-60780, IEC/IEEE 344-60980, IEC 60515.

- B-10 and BF3 proportional counters (source range).
- B-10 ionization chambers (intermediate and power range).
- Fission chambers (U-235) for source/wide/power range.

Mineral-insulated cables for harsh environments.

Neutron flux range: $0.1 - 2 \times 10^{10}$ nv (typical).



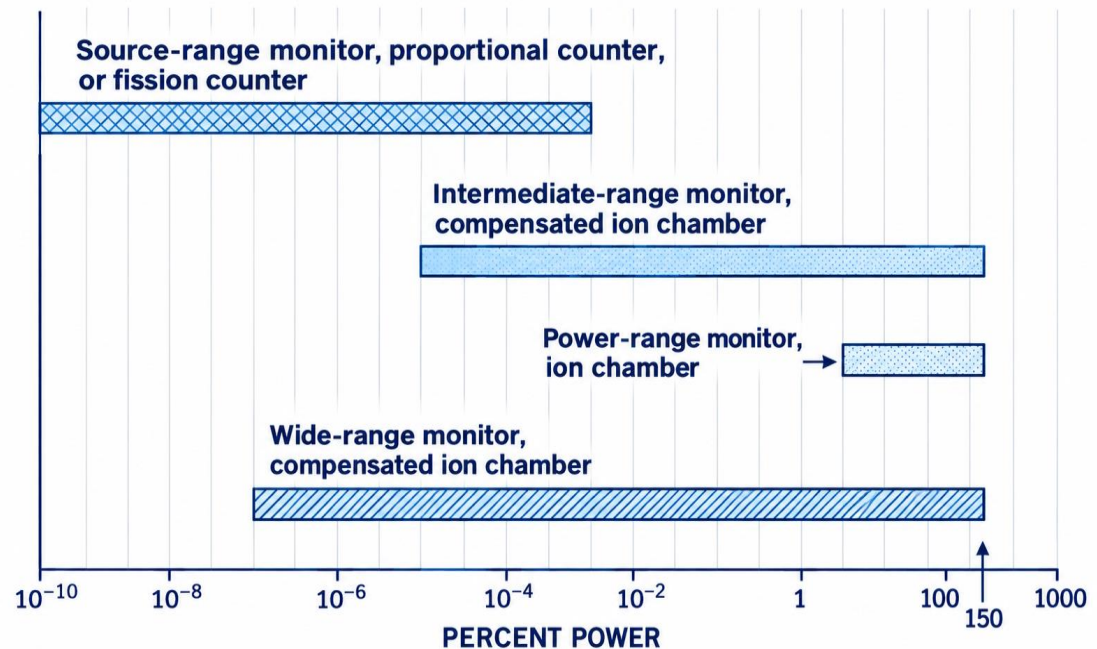
SRM: Source Range Monitor

IRM: Intermediate Range Monitor

LPRM: Local Power Range Monitor

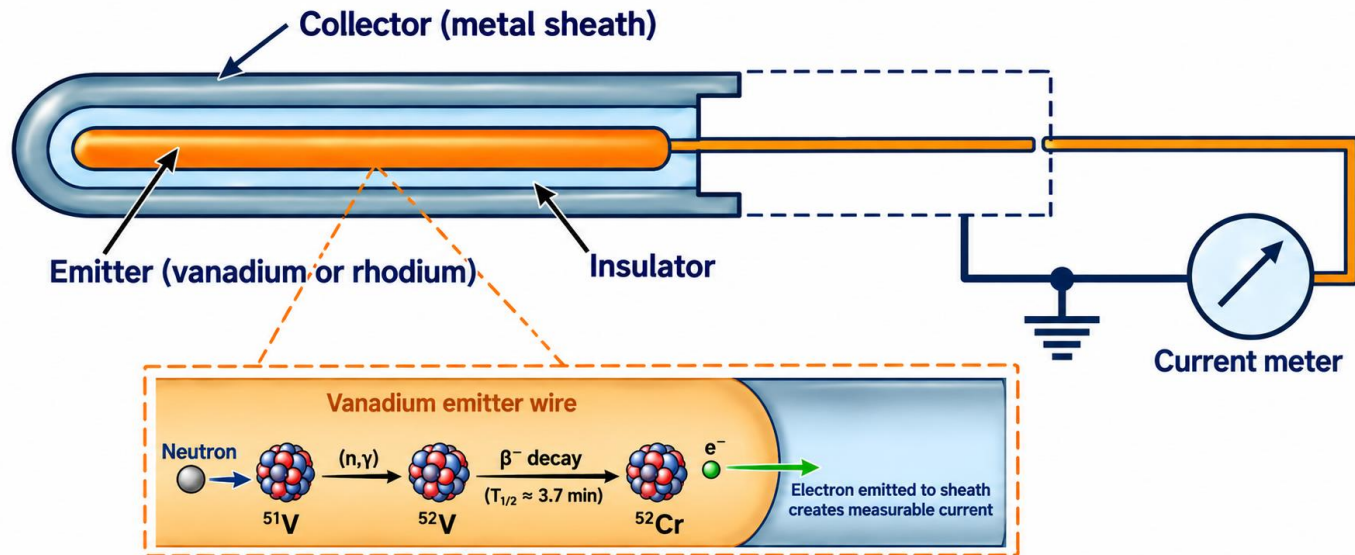
APRM: Average Power Range Monitor

- Boiling Water Reactors:
 - Source range monitors
 - Intermediate range monitors
 - Local power range monitors
 - Traversing in-core probes
- Pressurized Water Reactors:
 - Wide-range monitoring systems
 - Power range monitors
 - Moveable in-core detector systems



Source: Survey of neutron flux sensors for monitoring advanced reactor concepts operating with low neutron fluence rate and extended uninterrupted lifespans – INL (adapted)

- Metal based, no power needs, in-core detectors: an emitter wire and metal sheath, separated by insulation



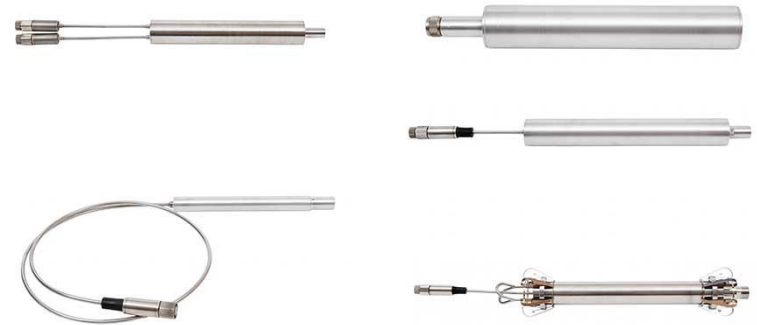
The WL-23226 is a commercially available delayed SPND from Mirion. [9]

- Flux Range: 10^9 to 10^{15} nv
- Response Time: 300s
- Max Operating Temp: 400°C
- Sensitivity: $1.1 \cdot 10^{-20}$ A/nv with Vanadium emitter
- Gamma Background: 2%



Exosens FC165 Ex-Core Fission Chamber:

- Pulse (Thermal): 0.12 cps/nv
- Current (Thermal): Reconfiguration required
- Current (Fast): 2.86×10^{-4} cps/nv
- Diameter: 25.4 mm
- Sensitive Length: 57 mm

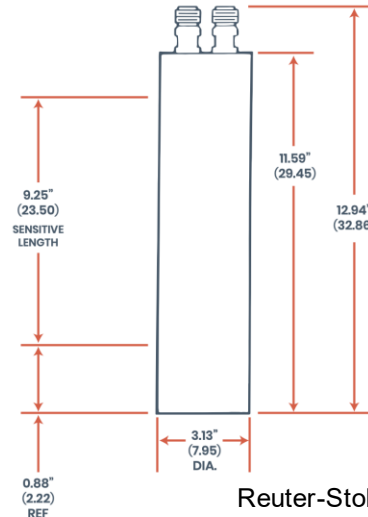


Exosens FC165

Exosens CFUR Miniature Fission Chamber:

- Pulse (Thermal): 8.0×10^{-6} - 1.5×10^{-4} cps/nv
- Current (Thermal): 9.2×10^{-19} - 1.7×10^{-17} A/nv
- Current (Fast): N/A
- Diameter: 1.5 mm
- Sensitive Length: 10 mm

TYPE HN CONNECTOR
MATES WITH ANY
SERIES HN PLUG,
SUCH AS MIL UG-59 AU



Exosens CFUR

Reuter-Stokes RS-C3-2510-114 Fission Chamber:

- Pulse (Thermal): 10^6 nv
- MSV (Thermal): 10^4 to 10^6 nv
- Max Operating Temp: 300° C
- Radiation Tolerance: Up to 10^6 R/hr (8,770 Gy/hr)
- Lifetime: 1.6×10^{20} nvt with a 10% drop in sensitivity
- Diameter: 8.02 cm

Reuter-Stokes RS-C3-2510-114



Exosens 28EB/20/13 BF₃ Proportional Counter:

- External Diameter: 12.5 mm
- Active Length: 280 mm
- Gas Pressure: 0.26 atm
- Operating Voltage: 930 V
- Neutron Sensitivity: 0.8 cps/nv



Exosens 28EB/20/13 BF₃ Proportional Counter

Exosens IN37 Compensated Ionization Chamber:

- Diameter: 38.1 mm
- Sensitive Length: 210 mm
- Sensitivity (Neutron): 1.4×10^{-14} A/nv
- Sensitivity (Gamma): 2.5×10^{-10} A/Gy/h



Exosens IN37 Compensated Ionization Chamber

Exosens IN38 Uncompensated Ionization Chamber:

- Diameter: 38.1 mm
- Sensitive Length: 210 mm
- Sensitivity (Neutron): 1.4×10^{-14} A/nv
- Sensitivity (Gamma): 2.5×10^{-10} A/Gy/h



Exosens IN38 Uncompensated Ionization Chamber



A few examples of new development

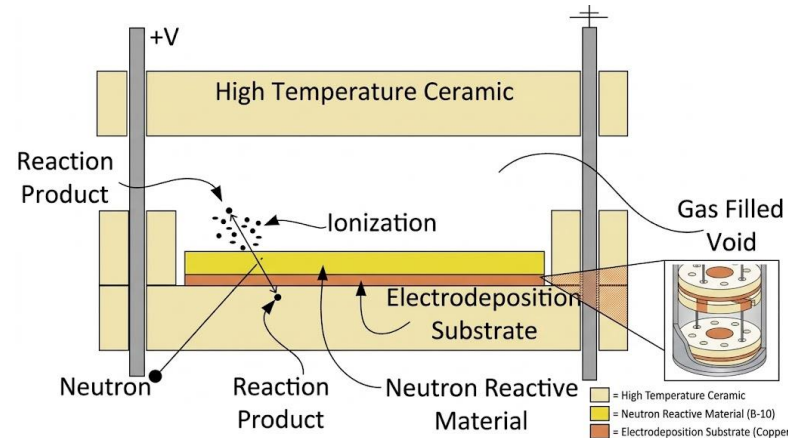


- Originally developed by Dr. Douglas McGregor at Kansas State University
- **MPFDs** are small-scale, in-core, Fission Chamber detectors
- They can read the neutron flux in real time without significantly affecting local flux

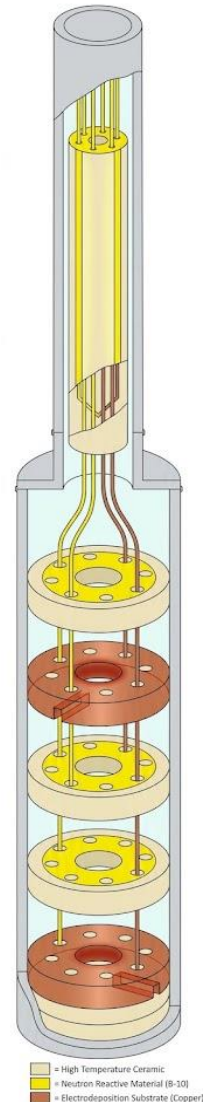
Specifications:

- Detector Array Length: Up to 3 m
- Chamber Outer Diameter: 3 – 4.7 mm
- **Chamber Size: 0.5 – 3 mm³**
- **Max Temperature: 1000°C**
- Number of Nodes: 1 – 4
- Coating: Up to 19% U-235
- Operation in Pulse, Current, and MSV

MPFD Node Cross Section



Images adapted from INL, enhanced with Google Gemini



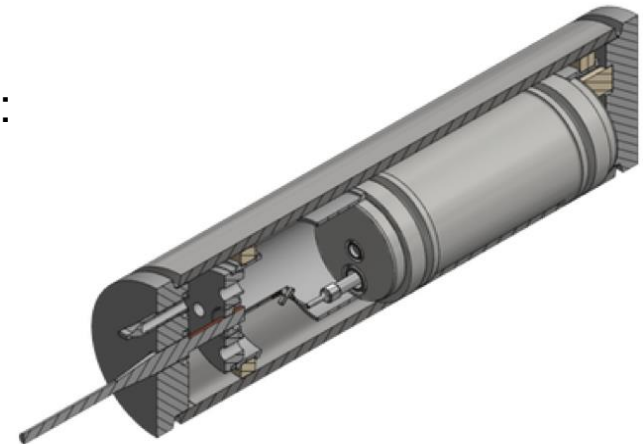
High- temperature fission chambers also remain a major development path.

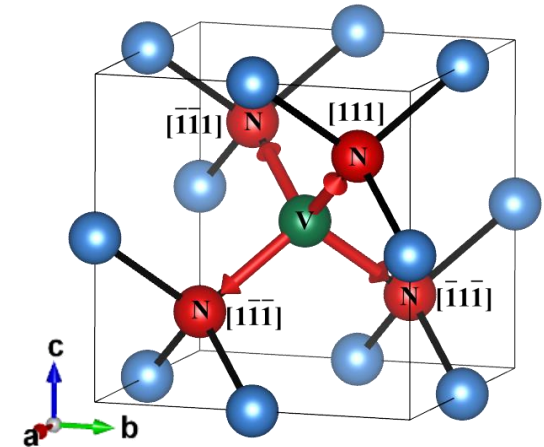
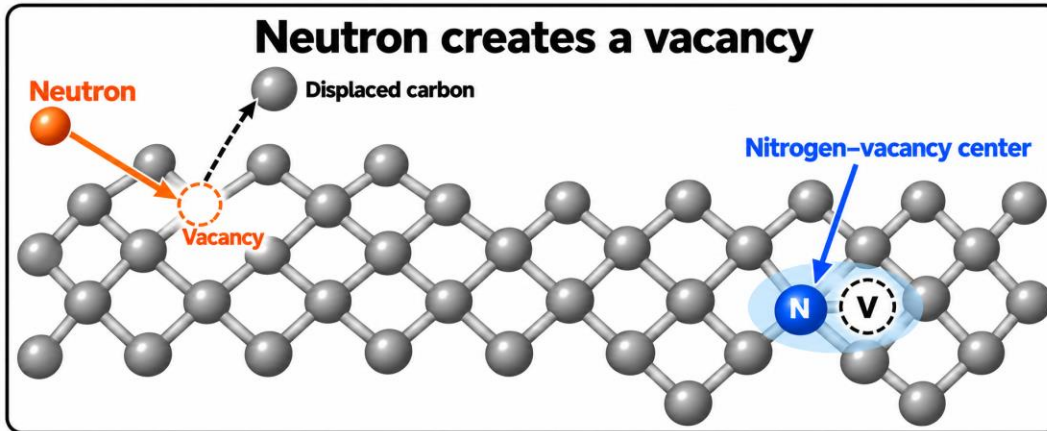
- Idaho National Lab reports heated irradiation tests at OSU Research Reactor from **600–850 °C**, including a miniature chamber seal failure at 750 °C—an example of why packaging can determine the operating limit.
- A commercial prototype has been developed by Curtiss-Wright and has undergone testing at ORNL

Liz McCrory, [*"ORNL puts Curtiss-Wright's next-gen fission chamber through high-heat evaluation," Oak Ridge National Laboratory, February 18, 2026*](#)

Curtiss-Wright High Temperature Fission Chamber:

- Pulse Mode Sensitivity: 0.033 cps/nv
- Current Mode Sensitivity: 7.67×10^{-15} A/nv
- MSV Mode Sensitivity: 2.40×10^{-27} A²/Hz/nv
- Max Operating Temp: 800° C
- Sensitive Length: 60 mm





WHAT IS AN Nitrogen Vacancy (NV) CENTER?

- Nitrogen atom replaces one carbon atom
- Immediately adjacent a vacancy (missing carbon atom)
- The lattice donates an electron to the center, creating an NV^- color center
- NV^0 (total 5, one unpaired e) and NV^- (total 6, two unpaired e)
- There are 3 main ground spin states in the NV^- center.

NV-center is a point defect.



Natural blue diamond:

- Boron impurity

Hope Diamond

45.52 carats (9.104 grams)



Green diamond:

- Carbon vacancies (GR1 centers)



Red diamond:

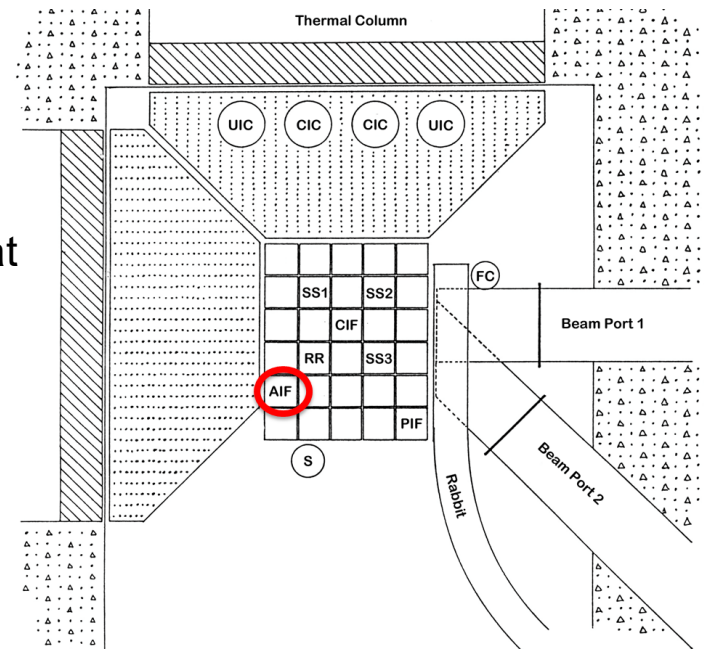
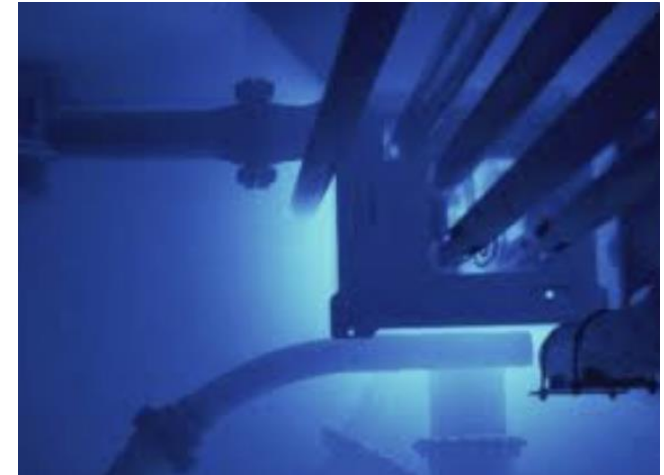
- NV center

Yellow diamond:

- Single substitutional nitrogen (C/P1 center)
- Three substitutional nitrogen atoms surrounding a vacancy (N3)

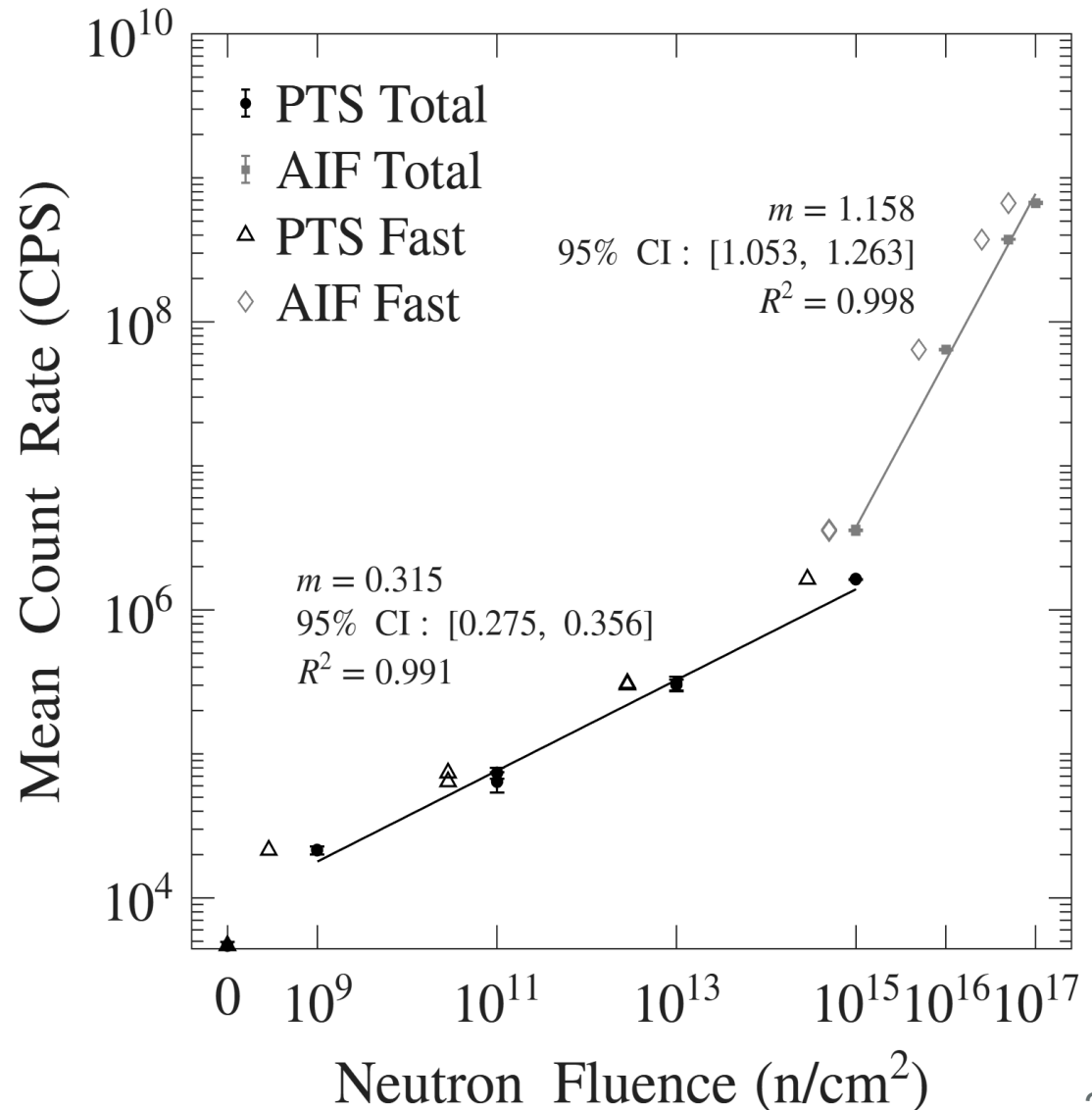
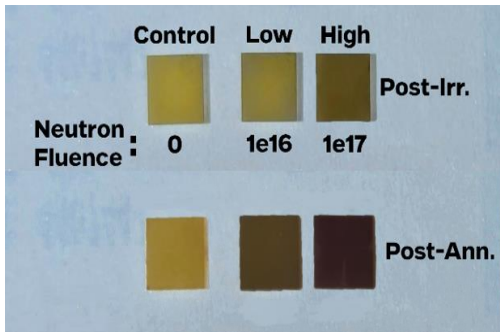


- Irradiated at The Ohio State University 500-kW Research Reactor
- Fluences (cm^{-2})
 - At Rabbit facility (PTS): 1×10^9 , 1×10^{11} , 1×10^{13} , 1×10^{15}
 - At Auxiliary Irradiation Facility (AIF): 1×10^{16} , 5×10^{16} , 1×10^{17}
- DPA (displacements per atom) at 10^{17} n/cm^2 :
 1.41×10^{-5} or 14.1ppm arc-dpa: vacancies that survive after initial recombination, i.e., after cascades settled [ENDF/B-III and PHITS]





1. “Linear” over 8 order of magnitude of neutron fluence from 10^9 to 10^{17}
2. “linear” over two segments, two different irradiation sites
3. Slope may reveal neutron energy information





Summary

- Gas-filled and metal based self-powered neutron detectors remain the most common solutions for commercial flux monitoring
- Developments in SMR, MMR, and fusion technology has created increased interests as well as technical challenges for future development of neutron flux detection
 - Long-term stability under high neutron fluence and high temperature.
 - Neutron–gamma discrimination in intense mixed radiation fields.
 - Detector sensitivity degradation and calibration drift.
 - Reliable packaging, electrical connections, and signal transmission.



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