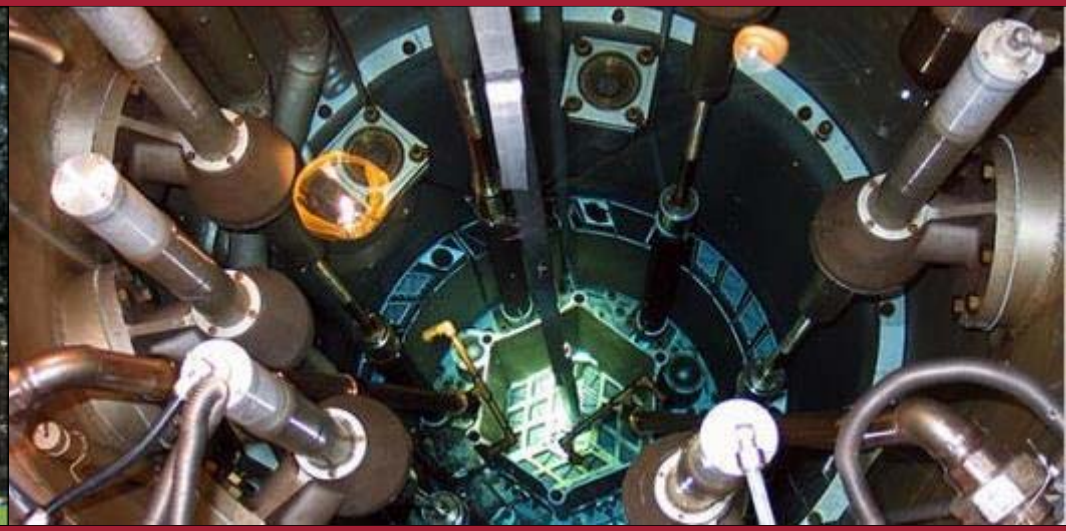
MIT NUCLEAR REACTOR LABORATORY

an MIT Interdepartmental Center



Task 3: Core Instrumentation Planning and Benchmarking

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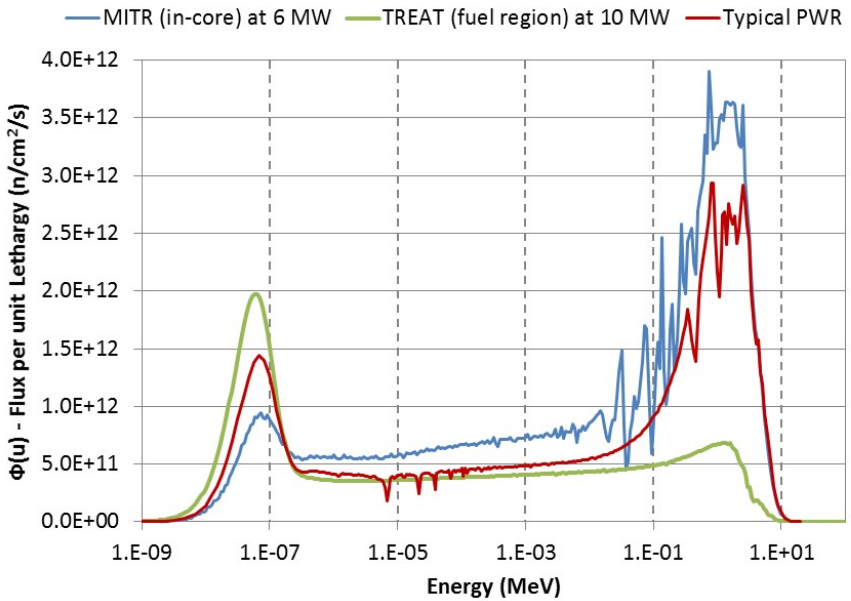
11/2017 – TREAT IRP Meeting, OSU

Task 3 Overview

- Instrumentation Plan
  - Identify TREAT core monitoring needs
  - Select sensors and requirements
  - Develop instrumentation plan

- Benchmarking
  - Design and selection of in-reactor instrumentation tests
  - Modeling (performance and safety)
  - Validation experiments
    - Steady-state and transient tests
  - Analyze data and develop instrumentation report

Neutron Flux Range – TREAT / MITR



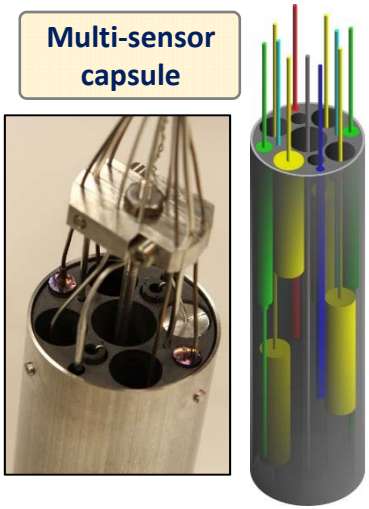
Unit: n/cm²/s	Thermal Flux (< 1 eV)	Fast Flux (> 0.1 MeV)	Total Flux
MITR at 100 kW	**6.17E+11**	2.22E+12	4.63E+12
MITR at 6 MW	3.70E+13	1.33E+14	2.78E+14
TREAT at 100 kW	**5.79E+11**	2.72E+11	1.45E+12
TREAT peaks at 18,000 MW	1.04E+17	4.90E+16	2.61E+17

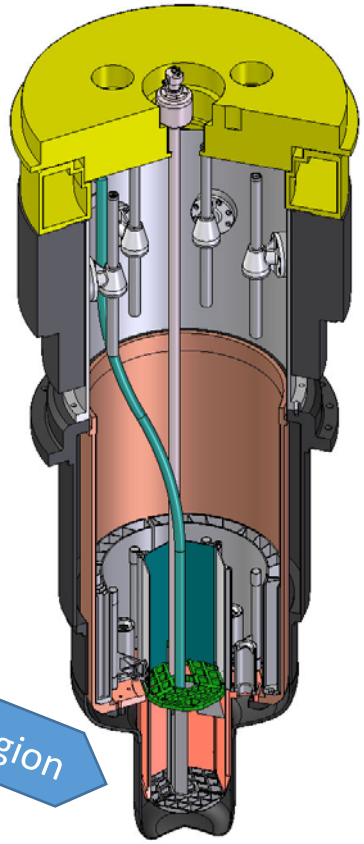
- **The TREAT neutron spectrum is notably more thermalized comparing to that of the MITR in-core position and of the typical PWR.**
- **The thermal flux (< 1eV) are comparable between the MITR and the TREAT, when they both operate at 100 kW power level.**
- **The 100 kW power level allows the MITR to operate with lid-open and natural circulation mode.**
- **The TREAT peak power level (18,000 MW) is significantly higher than that of the MITR full-power (6 MW) forced convection mode.**

Lead-out Experiments in the MITR

- Common framework available for instrumented in-core facility with multiple sensor types
- Streaming protection, EM noise reduction, and high-speed data acquisition
- Motorized or manually-actuated sensor packet positioning for axial scanning

Multi-sensor capsule





Instrumentation support below reactor top shield

Data acquisition and analysis during reactor operation

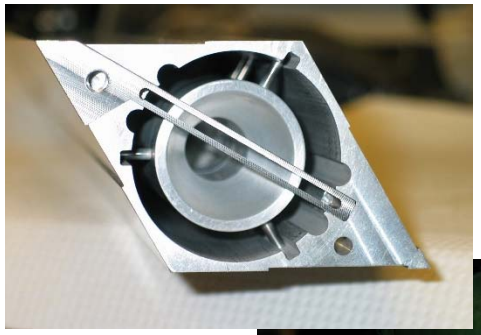
Irradiation Facilities

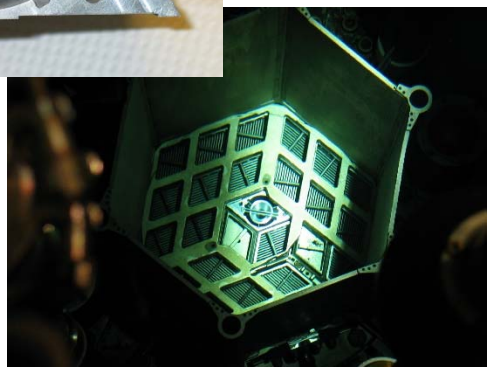
MITR

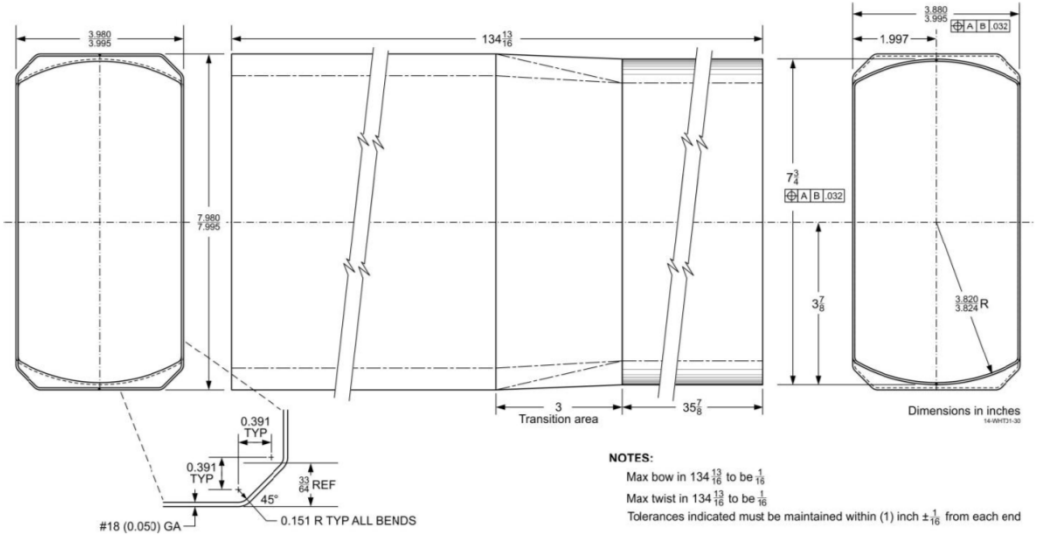
- Dedicated facility constructed for available AFTR dummy element (~2-inch diameter position)
- Strong heat sink to primary coolant (<50C)

TREAT

- M8CAL central experiment position (Mk III can)
- Larger diameter and height available than MITR
- Higher heat loading during transient

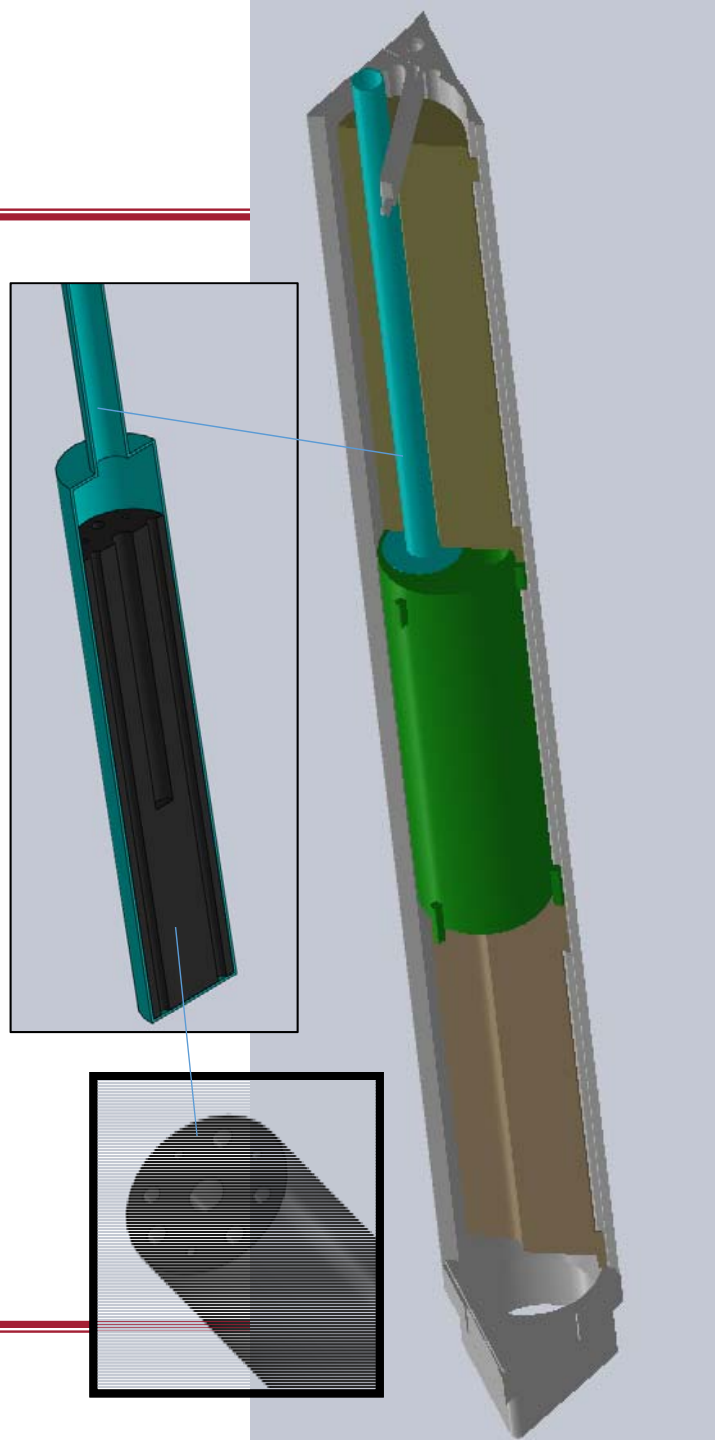






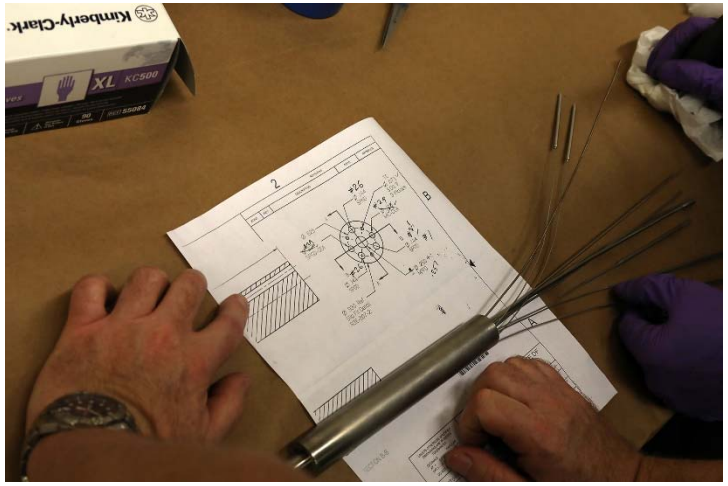
MITR Facility Design

- Both capsules are welded titanium shell with high-purity graphite liner
  - Sensor capsule 1.25 in OD
  - Activation capsule 0.625 in OD
- For activation capsule, may load each flux wire into vanadium for convenience
- Sensor capsule accommodates full active length of each sensor in the graphite
  - Minimize clearances to reduce thermal gradients
  - Lead-outs through ½-inch titanium riser – sealed at the top of the core tank to provide secondary encapsulation



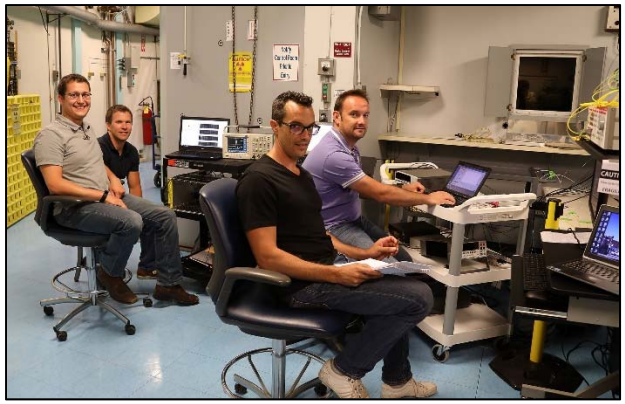
Fabrication and Installation

- Facility was assembled at MIT and inserted into the reactor on 7/24/2017
  - Multi-Pocket Fission Detector (MPFD)
  - Self-Powered Gamma Detector (SPGD) – four versions
  - Self-Powered Neutron Detector (SPND)
  - Miniature Ion Chamber
  - Thermocouples (K, T, and N-type)
- Lead-out sensors are contained in one capsule while activation materials are in a second, replaceable position

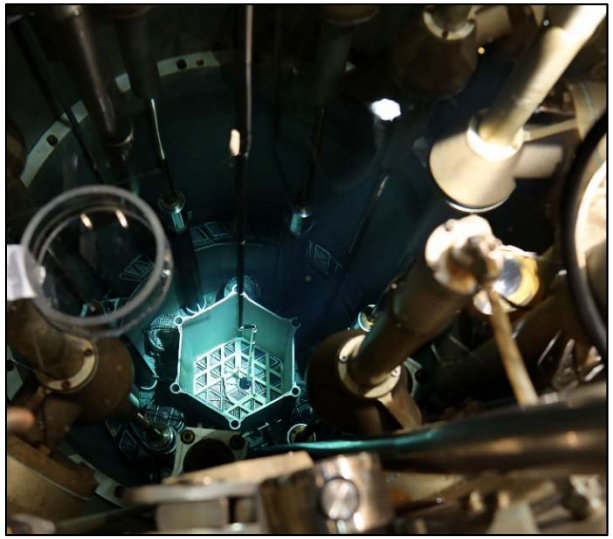


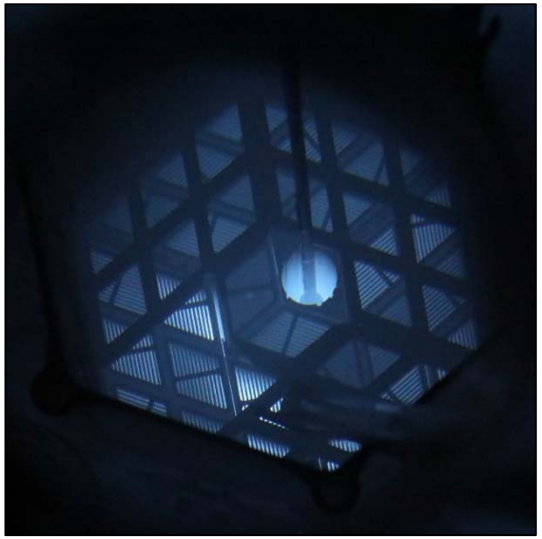
Sensor capsule stages of assembly – sensor placement, graphite holder loading, and welding

Flux Measurements



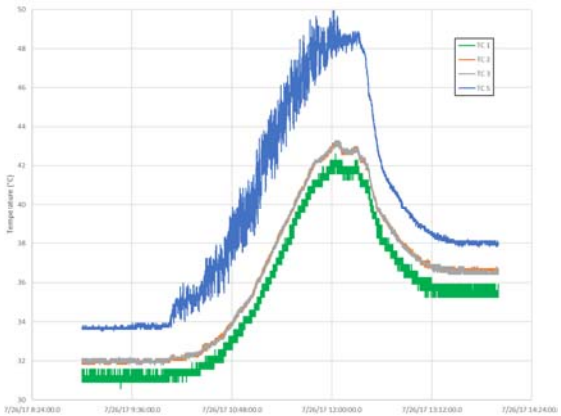
- Test plans for each stage of experiment operation took place over four days
  - Sensor shakedown
  - Steady-state at various power levels
  - Slow positive and fast negative transients
  - Concurrent pneumatic activation foils
- Feedback from initial tests used to make adjustments to DAQ and operations procedures



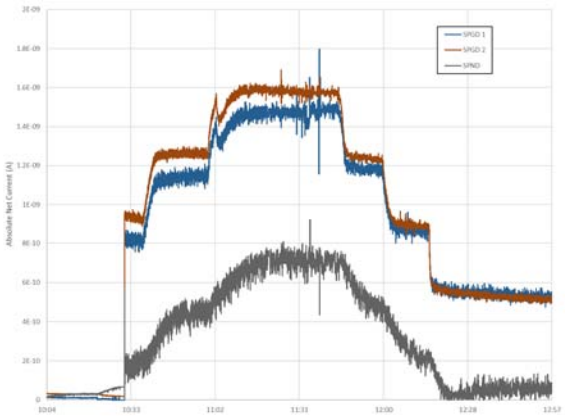


Sensor Data

- Experimenters were present from MIT, CEA, INL, and KSU
- Real-time data was gathered from all seven flux sensors and five thermocouples
- Data is now being processed to evaluate sensor performance during each phase of the test
- Valuable lessons learned on sensor design and behavior in a real reactor environment



TC data – water vs. sensors



INL SPD response

Test Plan (TP) Completed July 2017

7/26/17 – TP0: Steady-state Calibration

1000	RX **startup**
1003	RX hold for **10 minutes** at **10 kW, 20 kW, 40 kW, 60 kW, 40 kW, and 20 kW**
1215	RX **shutdown** via ARI (all rods/blades driven in simultaneously)

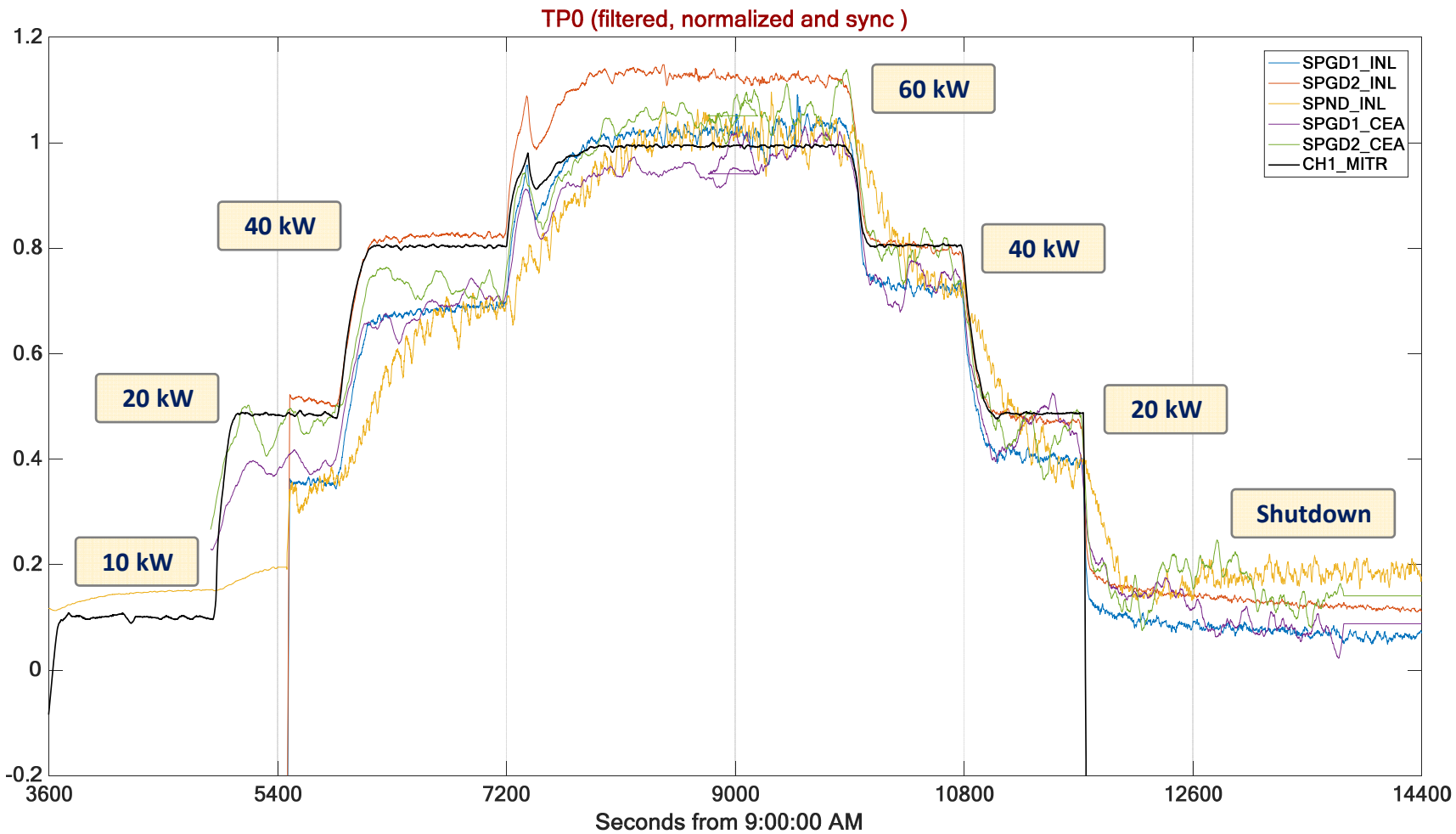
7/27/17 – TP1: Slow-positive and Fast-negative Transients

1000	RX **startup**
1020	RX hold for **10 minutes** at **10 kW**
1030	Drive **regulating rod** out for **2 minutes**, minimum 50s period (Slow-positive Transient)
1034	RX hold for **50 minutes** at **60 kW**
1130	**Drop one shim blade by releasing electromagnet** (Fast-negative Transient)
	Wait 5 seconds, then RX shutdown **via Minor Scram** (drop all blades)

7/28/17 – TP2: Slow-positive and Fast-negative Transients

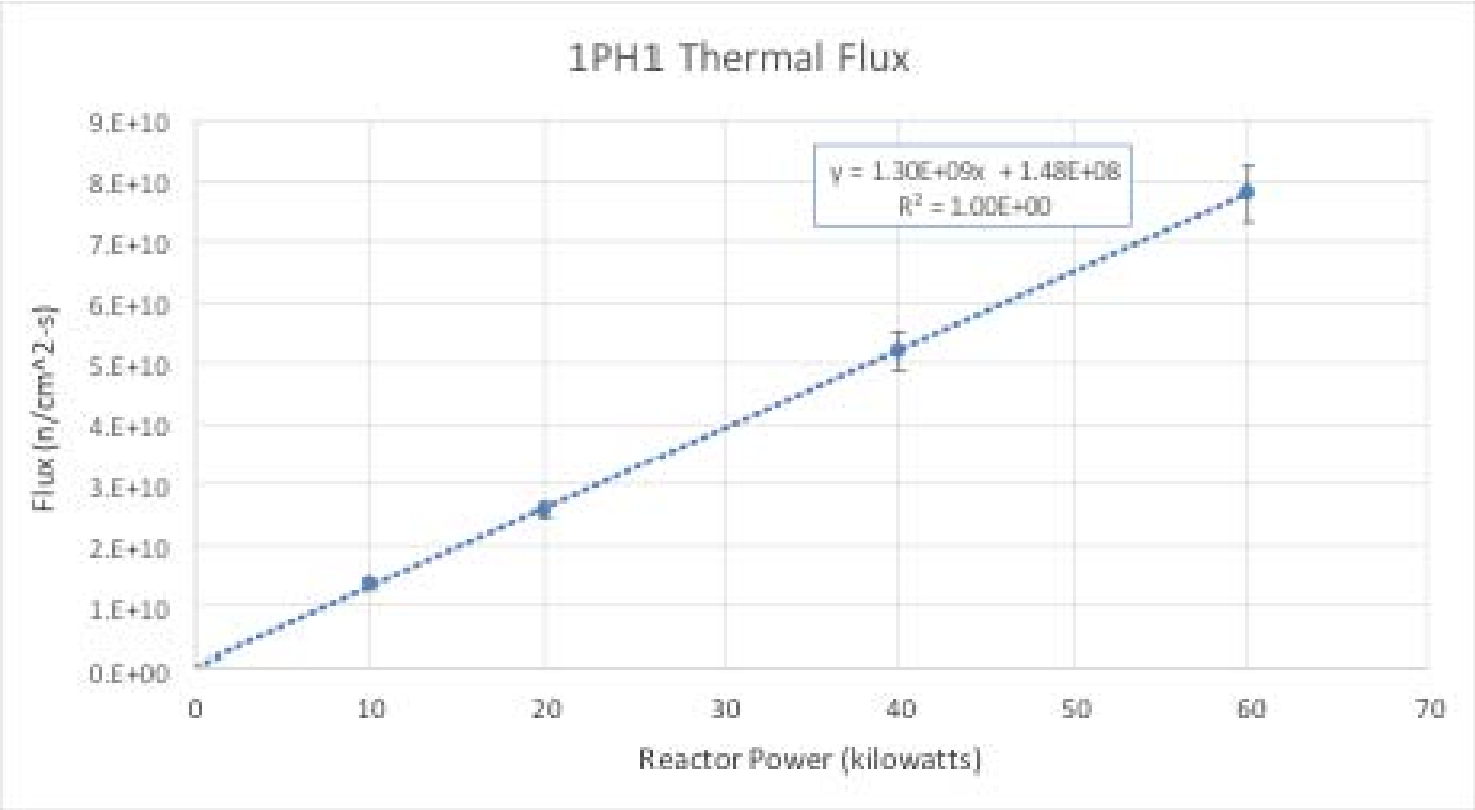
0900	RX **startup**
0930	RX hold for **10 minutes** at **10 kW**
0950	Drive **one shim blade** out for **2 minutes**, minimum of 50s period (Slow-positive Transient)
0955	RX hold for 50 minutes at **60 kW**
1045	**Drop one shim blade by releasing electromagnet** (Fast-negative Transient)
	Wait 5 seconds, then RX shutdown **via Minor Scram** (drop all blades)

TP0: Post-processed Data

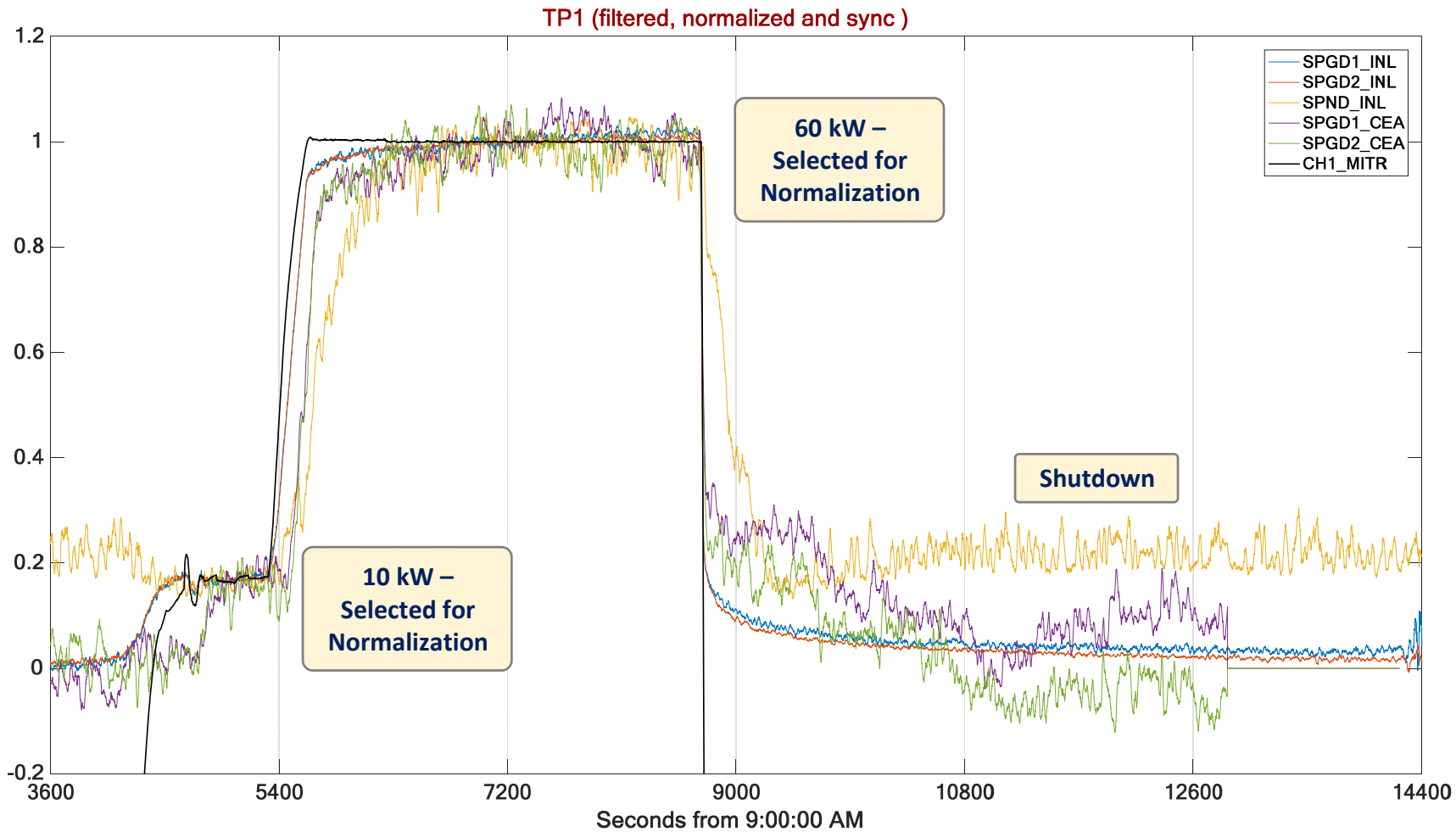


Neutron Flux/Power Verification

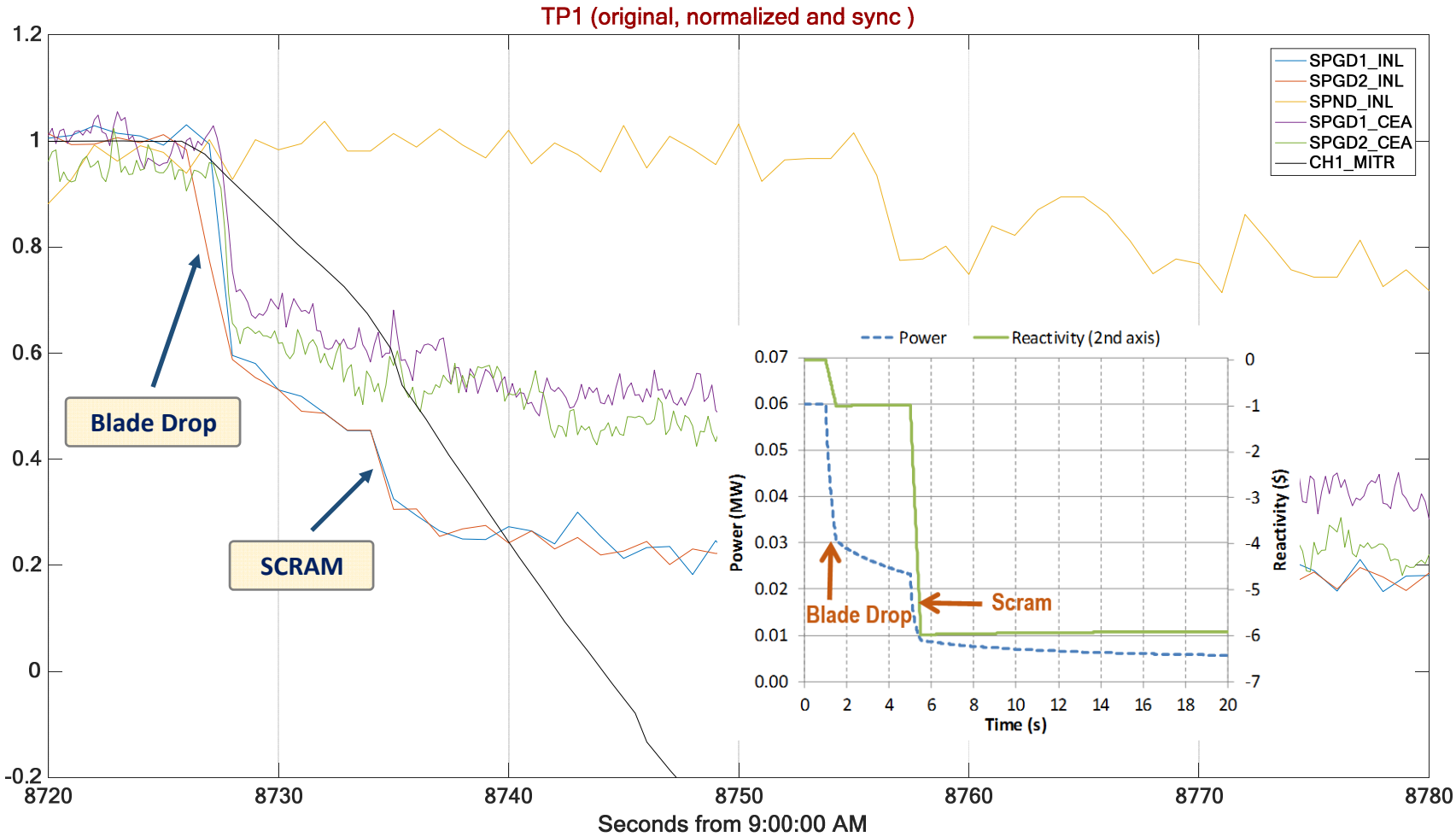
- Verification of reactor power using gold foil irradiation in 1” pneumatic tube.
- Irradiations were performed for multiple gold foils at each steady-state power while the in-core sensor thimble is installed.



TP1: Post-processed Data



TP1: Fast-negative Transient



Follow-On MITR Irradiation

- Planned modifications to MPFD and Miniature Ion Chamber sensors to improve performance
- Modified dummy fuel element to facilitate new positions
- New activation capsules
  - Fission wires – natural and depleted uranium prepared
  - Test fission wire NAA completed, data processing

Planned TREAT Irradiation

- Instrumentation capsule geometry designed for compatibility with M8CAL facility
- Components
  - Working on next set of sensors (MPFD, CEA)
  - Activation materials OK
- Coordination with INL staff to get test approval
  - Lead-out design
  - Fabrication
  - Delivery to INL

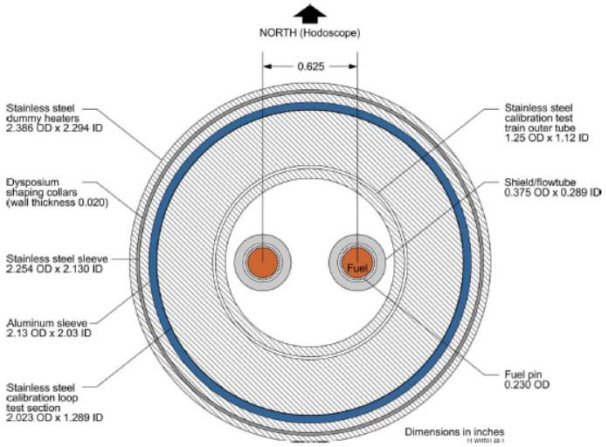
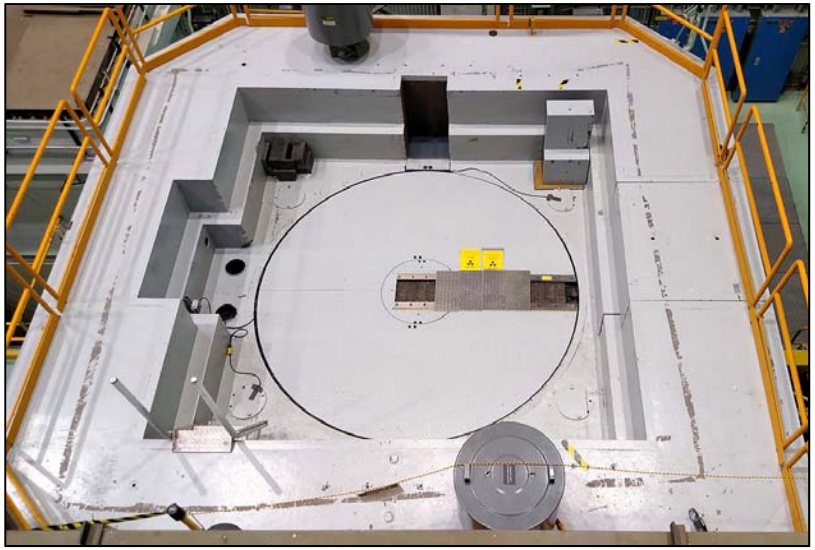


Figure 2.362. M8CAL Cross Section.



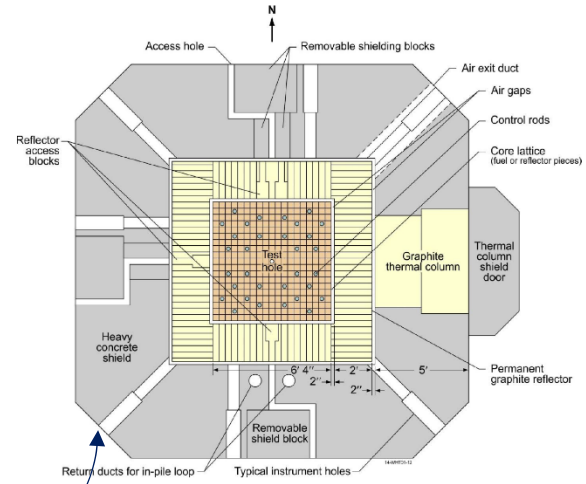
Backup Slides

Task 3: Core Instrumentation

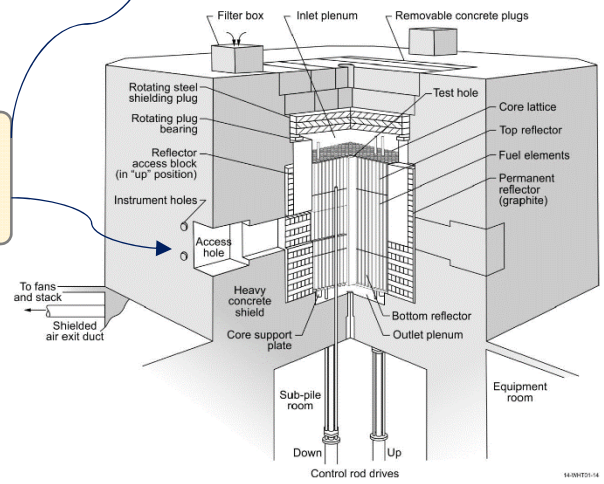
- 3.1 Instrumentation Plan
  - 3.1.1 Review TREAT core design and test plans *MIT*
  - 3.1.2 Identify core parameter monitoring needs *MIT*
  - 3.1.3 Determine applicable flux/measurement range *MIT*
  - 3.1.4 Select TREAT core instrumentation *MIT*
  - 3.1.5 Identify instrumentation calibration requirements *MIT*
  - 3.1.6 Develop TREAT core instrumentation plan *MIT*
- 3.2 Initial Benchmark Evaluation
  - 3.2.1 Develop Benchmark experimental plan using the MITR *MIT*
  - 3.2.2 Select test instrumentation *MIT*
  - 3.2.3 Design test assembly for OSTR and MITR *MIT*
  - 3.2.4 Conduct experiment safety review and approval *MIT*
  - 3.2.5 Perform core analysis with MCODE *MIT*
  - 3.2.6 Assemble and test data acquisition systems *MIT*
  - 3.2.7 Perform steady-state experiments at MITR *MIT*
  - 3.2.8 Perform steady-state experiments at OSTR *OSU*
  - 3.2.9 Perform transient experiments at MITR *MIT*
  - 3.2.10 Perform transient experiments at OSTR *OSU*
  - 3.2.11 Analyze experimental data *MIT*
  - 3.2.12 Evaluate core analysis and instrumentation measurement uncertainties *MIT*

TREAT Instrumentation

- During normal operation, used ion chambers and proportional counters located in radial instrumentation ports
  - Outside of permanent graphite reflector
- Six types of thermocouple-instrumented assemblies for various locations
  - Reflector graphite
  - Element surface
  - Mid-fuel
  - Normal and fast-response



14 6” Radial Instrumentation Ports



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Startup Testing and Calibration

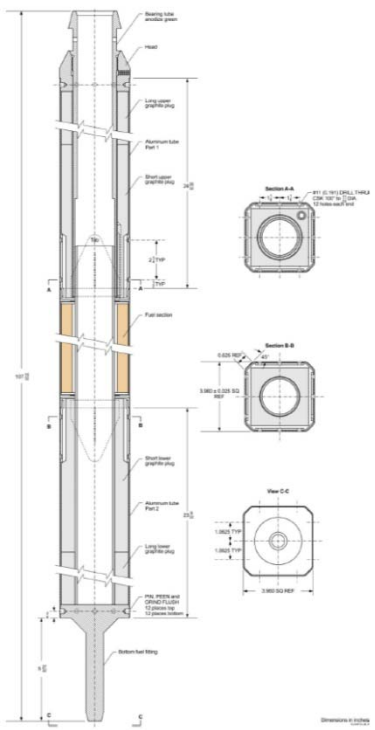
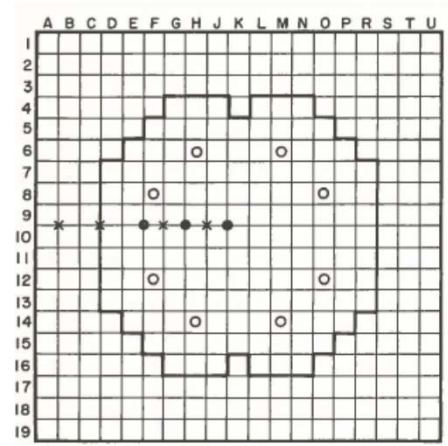


Figure 2.29. Vertical Access Hole Fuel Assembly.

ANL-6173

- During TREAT physics testing fission chambers were positioned within the core (coolant channels and element centers)
- Fission chambers, activation foils, and thermocouples moved to various radial and axial positions
  - Drive system mounted on reactor top shield to move detectors and foils
  - ***Core configuration dependent***
- Measurement of vital parameters
  - Temp and flux profile
  - Reactivity coefficients
  - Detector power calibration
  - Neutron spectrum
  - Transient response



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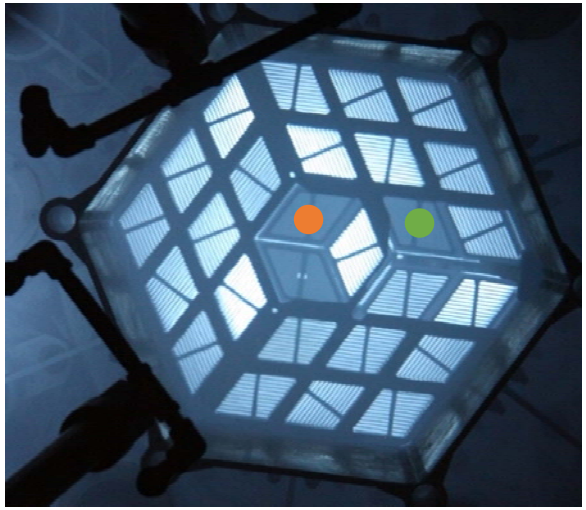
Instrument Tests at MITR

1. Potential Locations:

- A-ring (innermost ring) position
- 1 B-ring (middle ring) position



2. Static Measurements:

- The MITR operates at steady power of 60 kW (LSSS at 100 kW) with top lid open and natural convection mode.
- Different in-core and ex-core positions could be used for instrument test.

3. "Slow Positive" Transient:

- Withdrawing Regulating Rod (~ 200 mβ worth) to create a positive period more than 50 s (LSSS at 7 s).
- Steady power levels prior and after the transient are planned to be 600 W and 60 kW (LSSS at 100 kW).

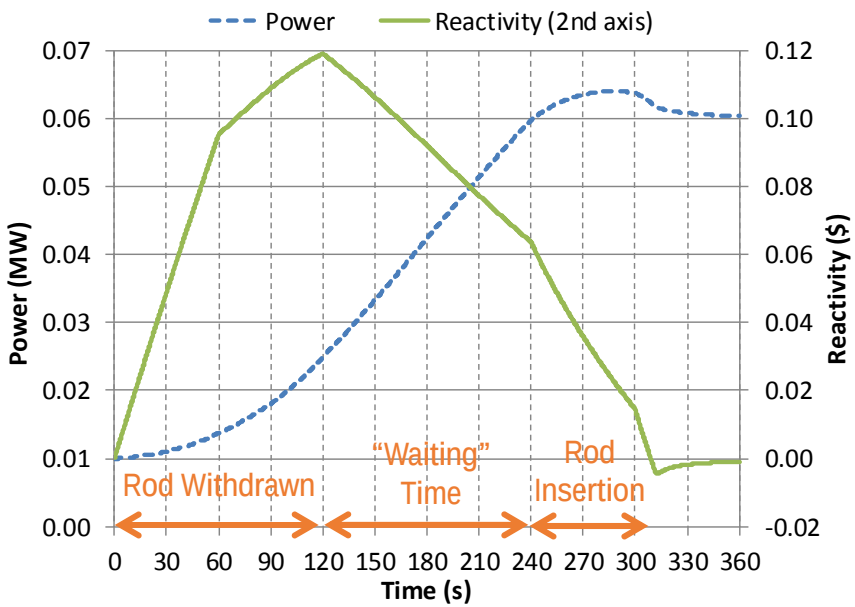
4. "Fast Negative" Transient:

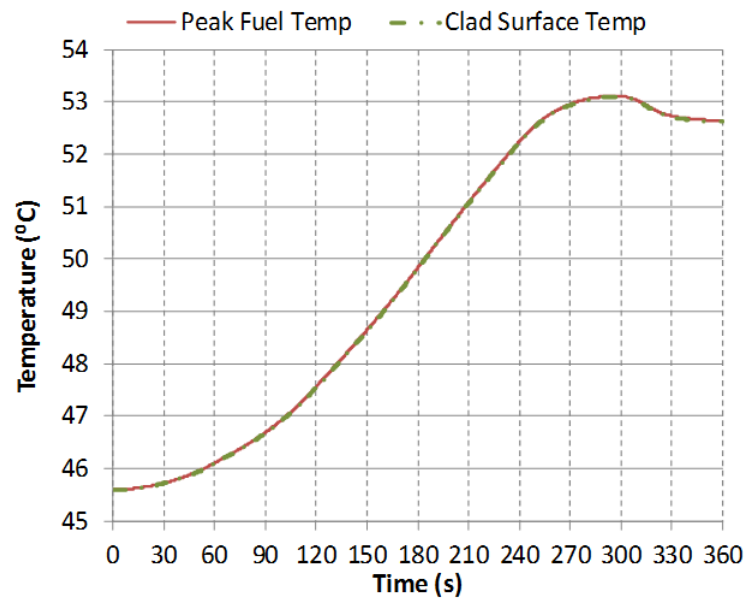
- Using Shim Blade Drop and Scram to create negative period less than 0.5 s.
- Steady power levels prior the transient is planned to be 60 kW (1% of MITR nominal power).

“Slow Positive” Transient

- Established by withdrawing the regulating rod. Total reactivity worth of ~ $ 0.18 with maximum insertion rate of ~ $ 0.10 / min
- Prior-transient steady-state at 10 kW (natural convection) Post-transient steady-state at 60 kW (natural convection)
- Safety analysis performed by PARET/ANL-7.6 beta

- **MITR thermal flux level at 60 kW is similar to TREAT thermal flux level at 100 kW, i.e., its instrumentation calibration power level.**
- **Slow transient (regulating rod withdrawn) creates a positive period of about 50 s.**
- **Peak fuel centerline and cladding surface temperatures overlap each other.**
- **No safety concern for the MITR is expected.**

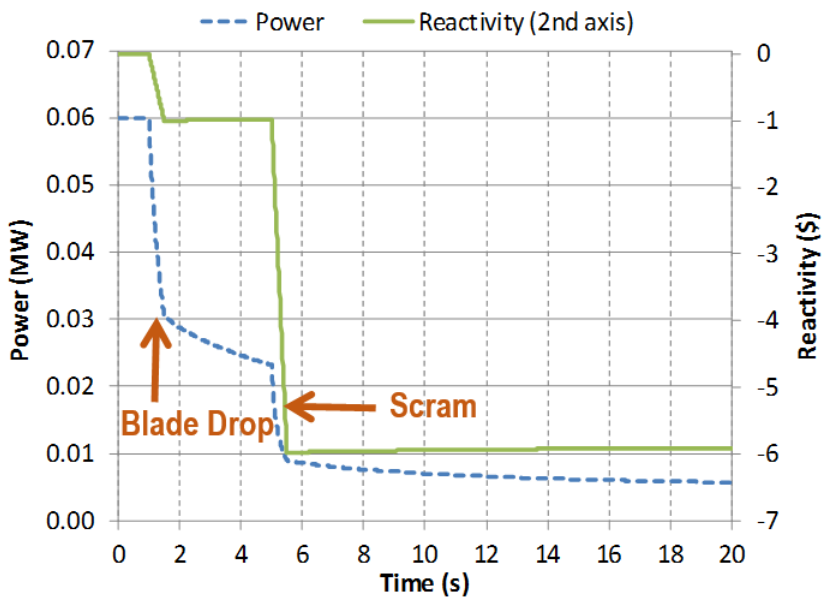


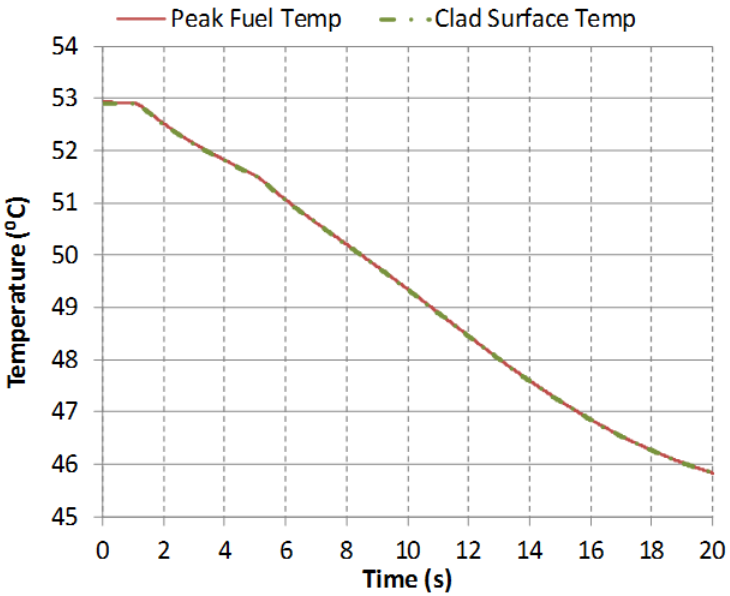


“Fast Negative” Transient

- Established by a blade drop followed with a Scram.
  Blade Drop: $ -1.0 insertion within 0.5 s
  Scram: Additional $ -5.0 insertion within 0.5 s
- Prior-transient steady-state at 60 kW (natural convection)
  Post-transient after 20 s reach ~ 5 kW (natural convection)
- Safety analysis performed by PARET/ANL-7.6 beta

- **Fast transient (blade drop / Scram) creates a negative period in magnitude of -100 ms.**
- **The 100 ms period provides benchmark conditions for those “fast response” detectors.**
- **All temperatures are well below light-water saturation point. Thus, coolant boiling is not anticipated to occur at any forms, hence no MITR Limiting Safety System Setting violation.**



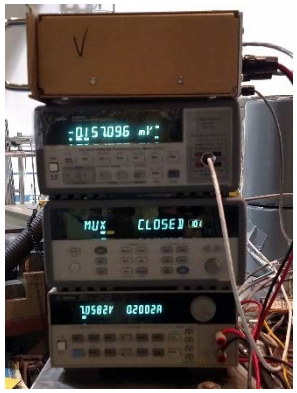


Instrument Calibration

- Pre-irradiation testing
  - Sealed gamma and neutron sources
  - Spectrum-characterized beamlines
- Neutron Activation Analysis Lab
  - Gold, Fe, 304 foils and wires for fluence
  - Cadmium ratio
- Verify instrument response curves
- Calibration requirements part of instrumentation plan

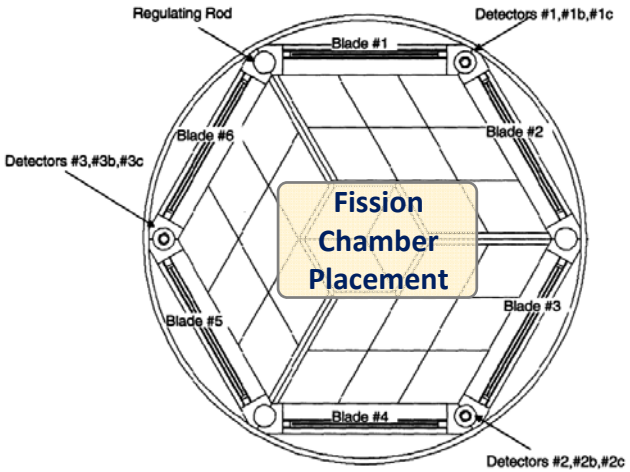
Multi-sensor Beamline

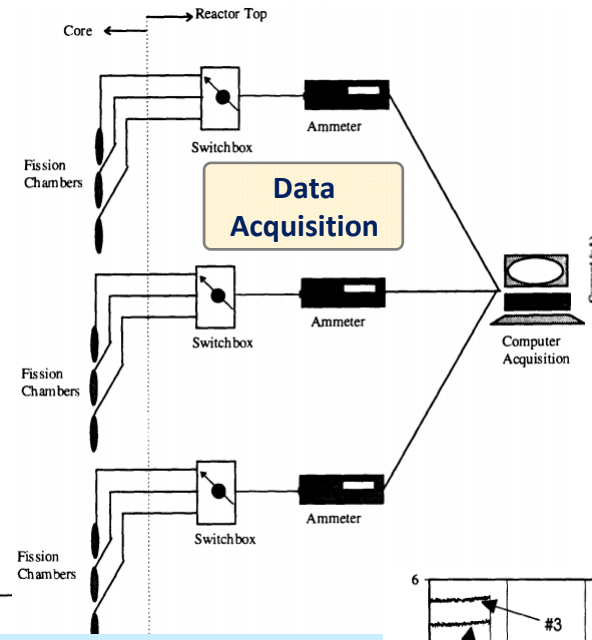
NAA Lab

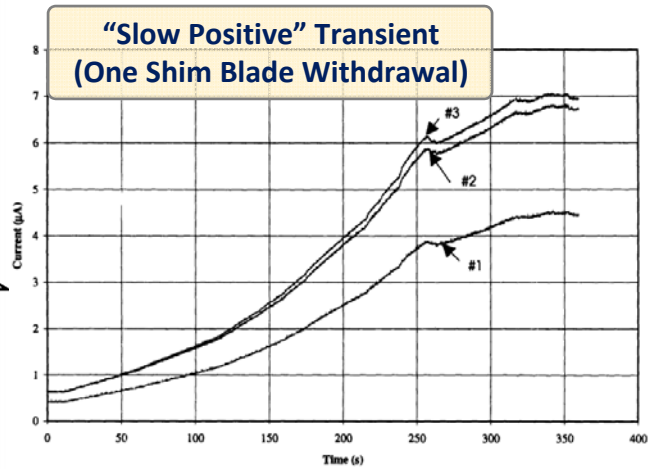


Existing calibrated instruments for rad work

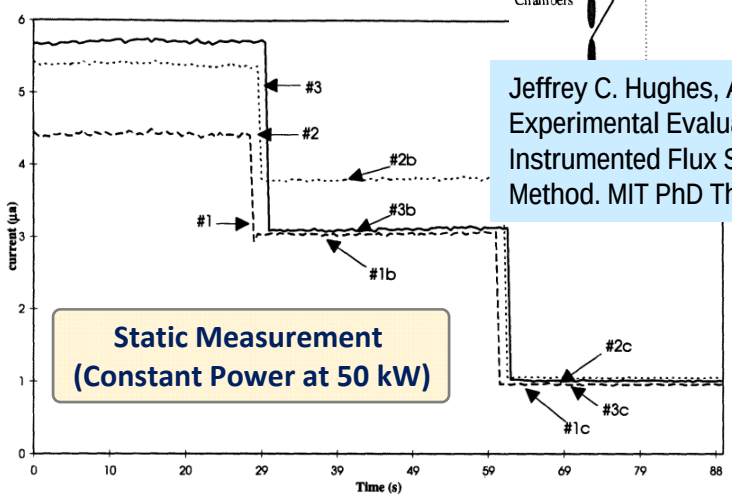
Past MITR Transient Measurements

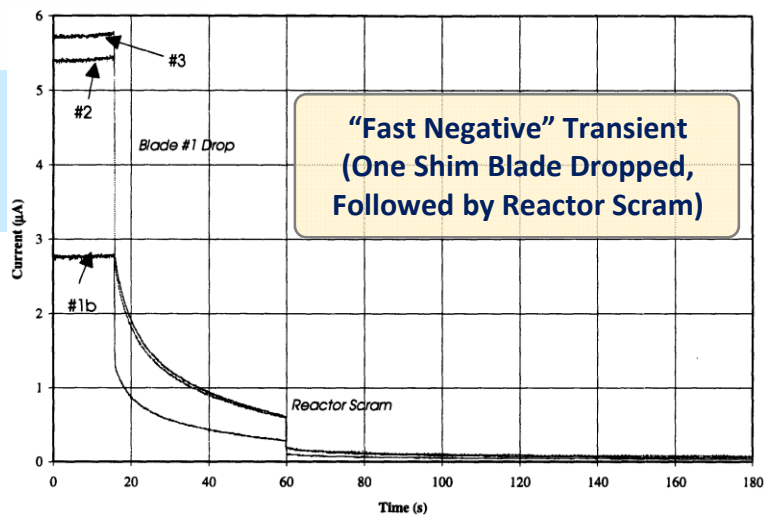






Jeffrey C. Hughes, An Experimental Evaluation of the Instrumented Flux Synthesis Method. MIT PhD Thesis, 1995.



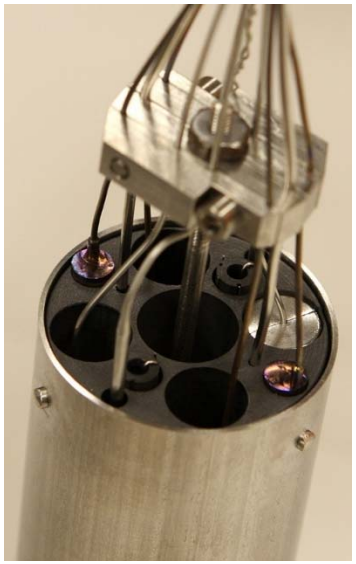


TREAT Preliminary Sample Matrix

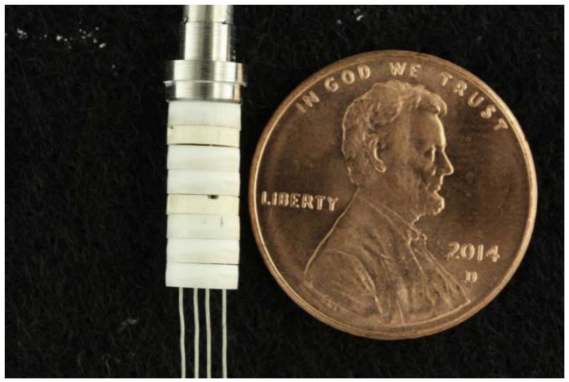
- Fission wires
  - **Natural uranium wire sealed in vanadium*
  - *Depleted uranium/Zr wire sealed in vanadium*
- Activation wires
  - *Al-0.2Co*
  - *Fe*
  - *Fe-18Cr-10Ni*
  - *Nb*
  - *Ti*
  - *Cu-2Au*
- Self-Powered Detectors
  - *Gamma (platinum, platinum-bismuth)*
  - *Neutron (vanadium)*
- Micro-Pocket Fission Detectors
  - *Uranium and thorium in a metal rod*
- Miniature Ion Chamber
- *Miniature Fission Chamber
  - *Enriched uranium in metal rods*

Mini FC

ULTRA



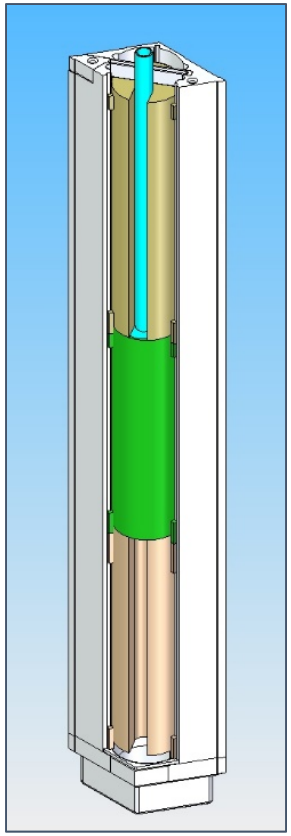
MPFD

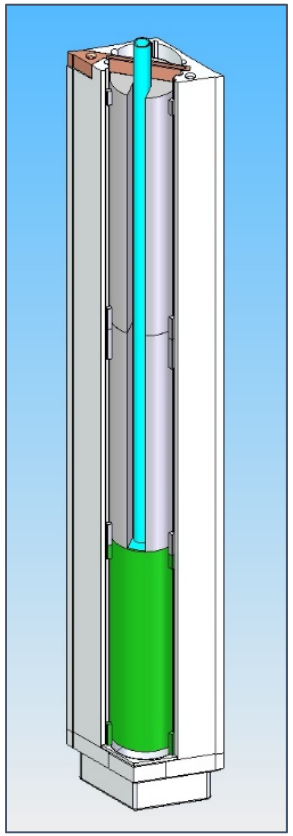


Sensor	Number	U-235 (mg)	Th-232 (mg)
Fission wire	2	0.55	-
Miniature fission chambers	1	0.04	-
MPFD	1	0.005	0.005
TOTAL	**4**	**0.60**	**0.005**

TREAT Preliminary Test Design

- In dummy element compatible with multiple experimental positions (A-1 and B-3)
- Two capsules
  - *Lead-out capsule for active sensors*
  - *Flux wire/foil capsule*
  - *Individually-replaceable*
- Thermocouples
  - *Type K and T thermocouples for higher resolution*
  - *On instrumentation tube to measure water temperature above core*
  - *Inside capsule to measure sensor temperature*
- Adjustable axial position
  - *By switching capsules with spacer, can position at different heights in core*
- Same securement as fuel element
  - *Hold-down via upper grid plate tab*





TREAT Re-positionable Ion Chambers