U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI Advanced Sensors and Instrumentation

Neutron Flux – INL

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

October 30 – November 2, 2023

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Idaho National Laboratory

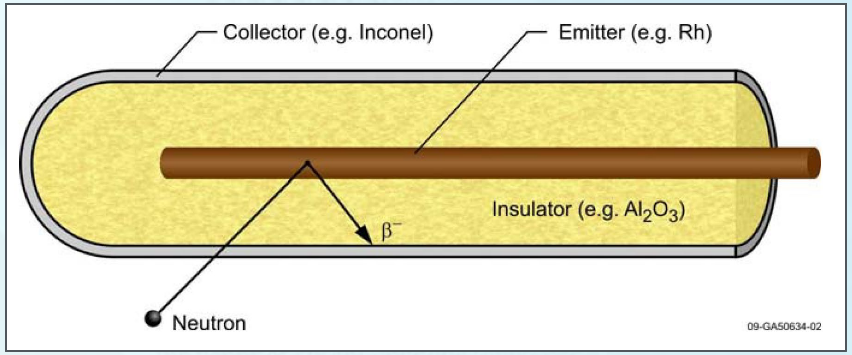
Project Overview (Summary)

The goal of the INL neutron flux work package is to evaluate and develop in-core neutron flux sensors for high-temperature applications in support of upcoming advanced reactor demonstrations.

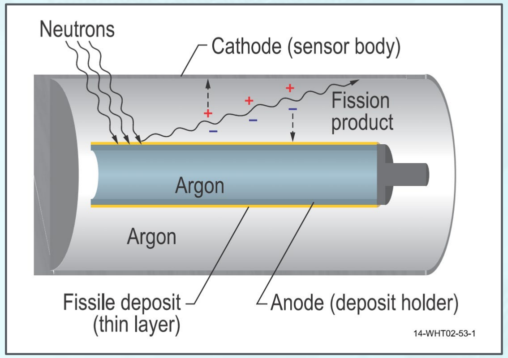
Technology of focus:

- Self-powered neutron detectors (SPND)
  - Material compatibility with temperatures above 900 ˚C
  - Passively generate electric current in a radiation field
  - Only operates in current mode

- Fission chambers (FC)
  - Material combability with temperatures ~800 ˚C
  - Detection of fission events via ionization of fill gas
  - Operates in pulse mode, Campbelling mode, and current mode



SPND overview sketch



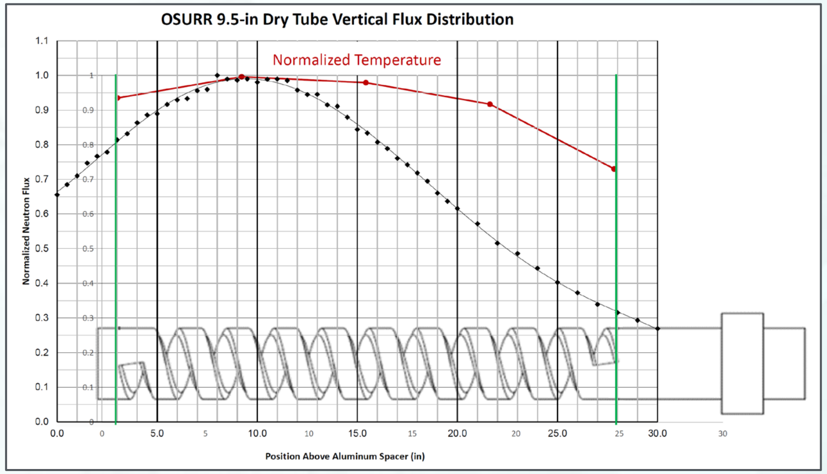
FC overview sketch

Project Overview (Summary)

The irradiation test work package focuses R&D activities to demonstrate deployment of sensors in relevant reactor conditions prior to incorporating them in high value fuels and materials experiments.

Capability of focus:

- Ohio State University Research Reactor (OSURR)
  - High temperature irradiation
  - 9.5” inner diameter dry-tube
  - 24” L × 2” inner diameter furnace



24” Furnace temperature and flux profile

24” Furnace at OSU

9.5” Dry-tube experiment

Project Overview (Schedule)

<u>FY 23 activities:</u>

- (Ongoing) M3CT-24IN0702011 – Performance benchmark of commercial fission chambers in elevated temperatures
  - (09/18/23 Irradiation) Performed at the OSURR
  - (11/31/23 Report Due) Report “Irradiation results of commercial and developmental fission chambers at high-temperatures”

- (Ongoing) M3CT-24IN0702012 – Demonstration of temperature compensation techniques for SPNDs operating in high temperature environments
  - (12/04/23 Scheduled) To be performed at the OSURR
  - (01/31/24 Report Due) Report “Testing of temperature compensation techniques for SPNDs operating at high temperatures”

- (Ongoing) M3CT-24IN0703048 – Complete second test at OSURR for high temperature characterization of neutron flux sensors
  - (11/15/23 Slides Due) Document “High-temperature testing of neutron flux sensors at OSURR”

Project Overview (Participants)

Participants:

INL	CEA	TP	OSURR
Kevin Tsai	Loïc Barbot	Marie Cuvelier	Andrew Kauffman
Michael Reichenberger	Grégoire de Izarra	Noor Ullah	Susan White
Geran Call		Tom Drury	Kevin Herminghuysen
			Matthew Van Zile

Heated experiment preparation

Technology Impact

Applications of in-core (built-in assembly or traversing in-core) and ex-core (out-of-vessel) detectors neutron flux sensors: controls, safety, or data acquisition.

- BWR considered heterogeneous
  - large array of in-core neutron detectors
  - monitor reactor power and distribution and ensure power peaks are within technical specifications
  - fixed in-core power range detectors with redundancy and calibrated against a movable detector system
- PWR considered homogeneous
  - strategically placed ex-core detectors are sufficient
  - included in-core detectors for power distribution mapping, ex-core detector verification/calibration
  - improved reactor monitoring – expand margin of operation

BF_3 Detector[1]	Sensitivity (cps/nv)	Max temperature (C)
WL-23274	4.5	120
WL-23069	6.5	120
WL-23058	13	120
WL-23057	19	120
WL-24427	10	107
WL-24425	25	107

[1]Mirion

B-10 Detector	Sensitivity (cps/nv)	Max temperature (C)
CPNB25[1]	4	200
CPNB28[2]	5	200
CPNB45[1]	8	200
CPNB48[1,2]	10	200
RS-C1B-1210-135[4]	3.6E-14 A/nv	200
RS-C2B-0808-129[4]	1.7E-14 A/nv	200

[1]Mirion
[2]Photonis
[3]Framatome
[4]Reuter-Stokes Baker Hughes

Fission Chamber	Sensitivity		Max temperature (C)
	cps/nv	A/nv	
CFUM11[1]	0.1	1E-14	250
CFUM18[1,2]	0.1	1E-14	250
CFUM21[1]	0.01	1E-15	250
CFUE24[1]	0.01	1E-15	400
CFUE32[1]	0.001	1E-16	600
WL23110[2]	0.18		300
RS-C6-04X0-20X[3]	2.1E-3		315

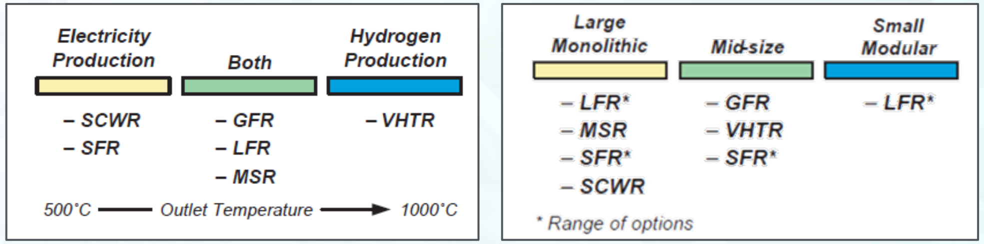
[1]Photonis
[2]Mirion
[3]Reuter-Stokes Baker Hughes

Technology Impact

This work evaluates commercial and developmental neutron flux sensors at high-temperature environments to support their adoption by advanced reactor developers.

Examples:

- Natrium (TerraPower) – more than 350 ˚C
- Xe-100 (X-Energy) – 750 ˚C
- KP-FHR – 650 ˚C
- eVinci (Westinghouse Nuclear) – 650 ˚C
- BANR (BWX Technologies) – target 1000 – 1400 ˚C
- MCFR/MCRE (SC/TP) – 600 ˚C



"A Technology Roadmap for Generation IV Nuclear Energy Systems, U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum", GIF-002-00, 2002

Overview of Generation IV Systems

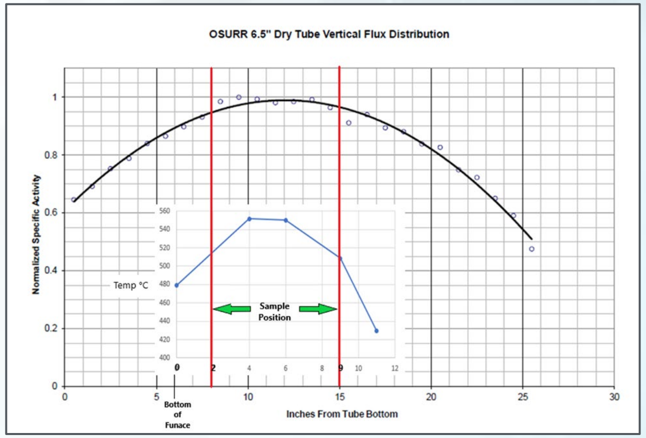
System	Neutron spectrum	Coolant	Outlet Temperature ˚C	Fuel cycle	Size (MW_e)
VHTR (Very-high-temperature reactor)	Thermal	Helium	900-1000	Open	250-300
SFR (Sodium-cooled fast reactor)	Fast	Sodium	500-550	Closed	50-150 300-1500 600-1500
SCWR (Supercritical-water-cooled reactor)	Thermal/fast	Water	510-625	Open/ closed	300-700 1000-1500
GFR (Gas-cooled fast reactor)	Fast	Helium	850	Closed	1 200
LFR (Lead-cooled fast reactor)	Fast	Lead	480-570	Closed	20-180 300-1200 600-1000
MSR (Molten salt reactor)	Thermal/fast	Fluoride salts	700-800	Closed	1000

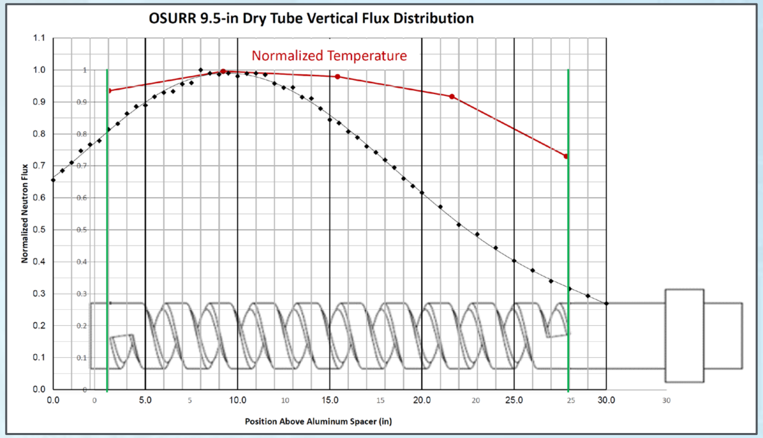
https://www.gen-4.org/gif/jcms/c_9353/systems

Results and Accomplishments

OSURR Heated Irradiation

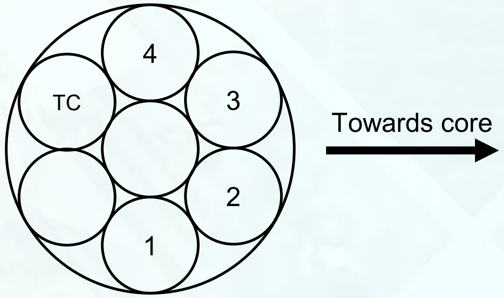
- Increased experiment size to accommodate sensors
  - Furnace ID: 1.25” → 2”
  - Furnace Length: 11” → 24”
  - Dry-tube: 6.5” → 9.5”





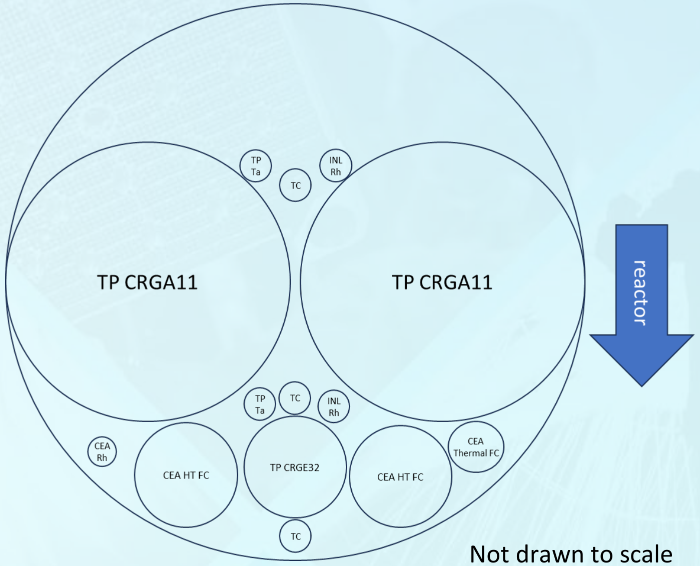
FY 22 Experiment

Sensor	Sensitive Region in tube height (in.)	Tube position
PH U5 FC	13 – 13.4	4
PH U8 FC	11.6 – 12	2
CEA U5 FC	12.4 – 12.6	3
CEA Rh-SPND	9.2 – 11.2	1



FY 23 Experiment

Sensor	Probe tip location (in.)*
(TP) CRGA11 x2	3
(TP) CRGE32	4.5
(CEA) HT FC x2	4.5
(CEA) Thermal FC	5
(CEA) Thx Rh-SPND	4.5
(INL) Mirion Rh-SPND	4.5
(TP) Mirion Ta-SPND	0
Type K #1	3
Type K #2	6
Type K #3	9

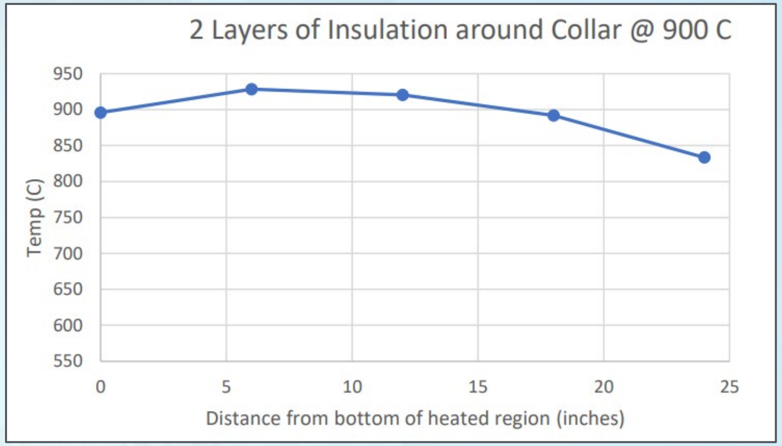


Not drawn to scale

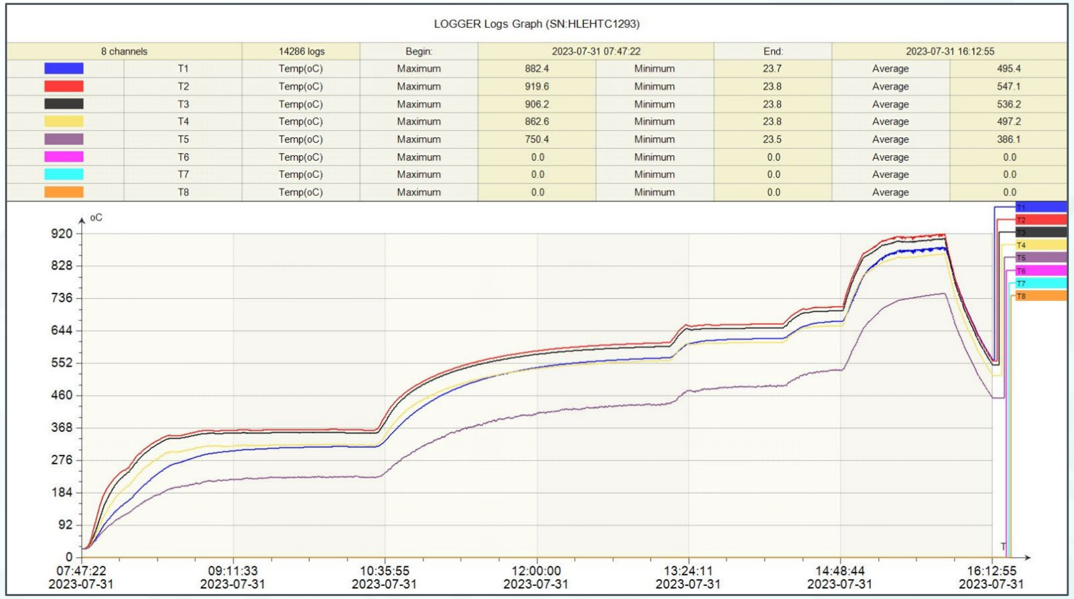
Results and Accomplishments

Furnace Performance Testing

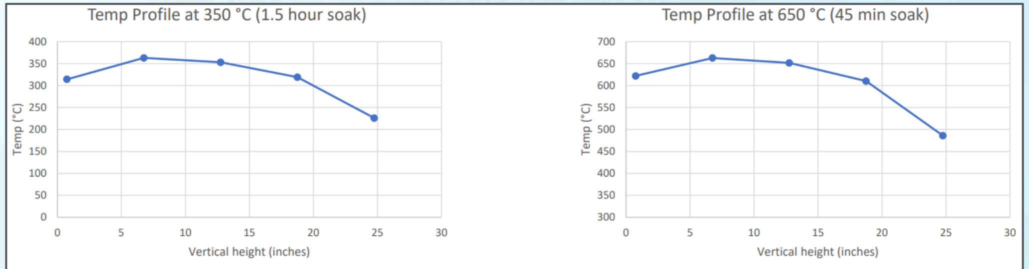
- Measure heating rates and temperature profiles on the larger furnace
- Improved temperature distribution with insulation testing

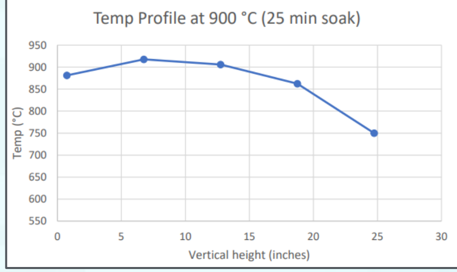


Insulated Temperature distribution



Heat rate testing results





Profile	350 °C	650°C	900°C
Height	Temp (°C)		
0.75	314.2	622	881.2
6.75	363	662.7	917.7
12.75	353	651.5	905.9
18.75	319.1	610.2	862.3
24.75	226	486	749.8

Initial temperature distribution results

Results and Accomplishments

Irradiation Plan

- 3 days of irradiation
  - Days 1 and 2 are for testing sensor operability at relevant temperatures
  - Day 3 is to test sensor limits and identify failure points

Day 1 Experiment

Power	Duration	Temperature
100 W	1 hr	Ambient
100 W/ 1 kW/ 10 kW/ 100 kW/ 200 kW	15 min each (+5 min per power change)	Ambient
1 kW	1 hr	Heat to 350 C
1 kW/ 10 kW/ 100 kW/ 200 kW	15 min each (+5 min per power change)	350 C
1 kW	1 hr	Heat to 600 C
1 kW/ 10 kW/ 100 kW/ 200 kW	15 min each (+5 min per power change)	600 C

Day 2 Experiment

Power	Duration	Temperature
100 W	1 hr	Ambient
100 W/ 1 kW/ 10 kW/ 100 kW/ 200 kW	15 min each (+5 min per power change)	Ambient
1 kW	1 hr	Heat to 650 C
1 kW/ 10 kW/ 100 kW/ 200 kW	15 min each (+5 min per power change)	650 C
1 kW	1 hr	Heat to 700 C
1 kW/ 10 kW/ 100 kW/ 200 kW	15 min each (+5 min per power change)	700 C

Day 3 Experiment

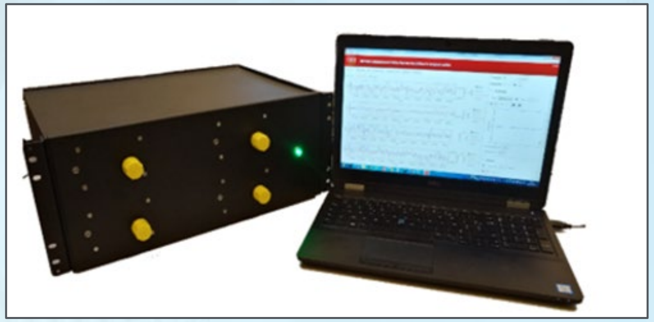
Power	Duration	Temperature
100 W	5 min each (+5 min per temperature change)	Ambient/ 600 C/ 650 C/ 700 C/ 750 C
100 W/ 1 kW/ 10 kW/ 100 kW/ 200 kW/ 450 kW	15 min each (+5 min per power change)	750 C
1 kW	1 hr	Heat to 850 C
1 kW/ 10 kW/ 100 kW/	15 min each (+5 min per power change)	850 C
1 kW	1 hr	Heater off

Results and Accomplishments

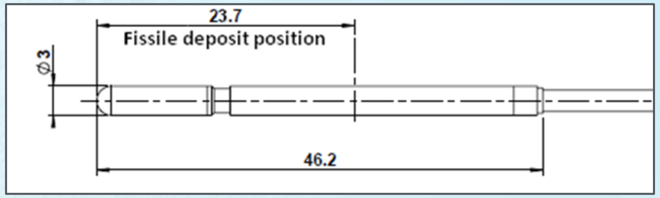
Fission Chamber Setup

- Electronics used with the I-TECH MONACO acquisition system
  - Pulse, Campbelling, and current mode simultaneously available
  - Counting curve availability
  - Built in oscilloscope for pulse shape analysis

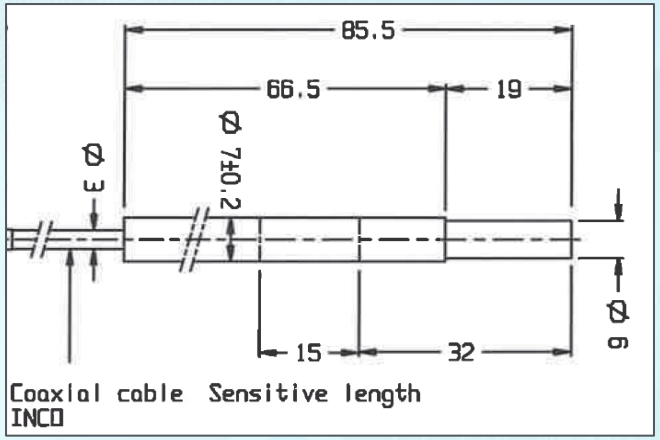
- Fission Chamber tested:
  - 3mm U-235 fission chamber based on CFUR64
    - Rated 400˚C
    - Specific CEA deposit: 1 µg U-235
    - Pulse mode specific – tested FY 22 to 350˚C
  - 7mm U-235 fission chambers based on CFUE43
    - Rated 600˚C
    - Commercial deposit: 170 µg U-235
    - Campbelling mode specific



MONACO System



Schematic of 3mm FC

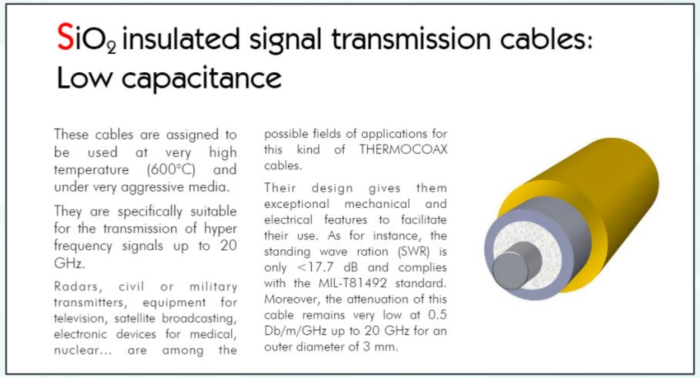


Schematic of 7mm FC

Results and Accomplishments

Fission Chamber Results

- 3mm U-235 fission chamber (FC-2349)
  - Noise reduction technique from FY-22 testing was still applicable
- 7mm high temperature fission chamber (HT-FC-1 and HT-FC-2)
  - Detector noise too large – pulse mode operation not possible
  - Multiple attempts made to reduce noise
- Final conclusion – improper detector cabling was used
  - 3mm fission chamber has the transmission cable and was able to reduce noise
  - 7mm chambers did not have the same cabling and was susceptible to noise from reactor controls



SiO_2 insulated signal transmission cables: Low capacitance

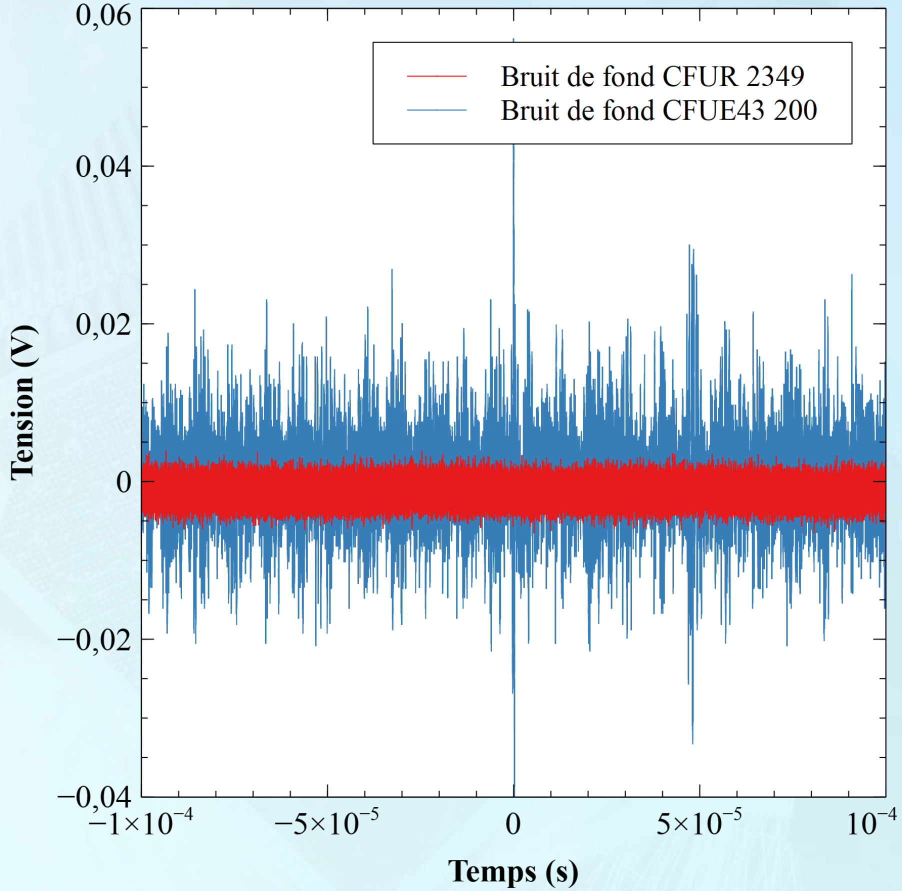
These cables are assigned to be used at very high temperature (600°C) and under very aggressive media.

They are specifically suitable for the transmission of hyper frequency signals up to 20 GHz.

Radars, civil or military transmitters, equipment for television, satellite broadcasting, electronic devices for medical, nuclear... are among the possible fields of applications for this kind of THERMOCOAX cables.

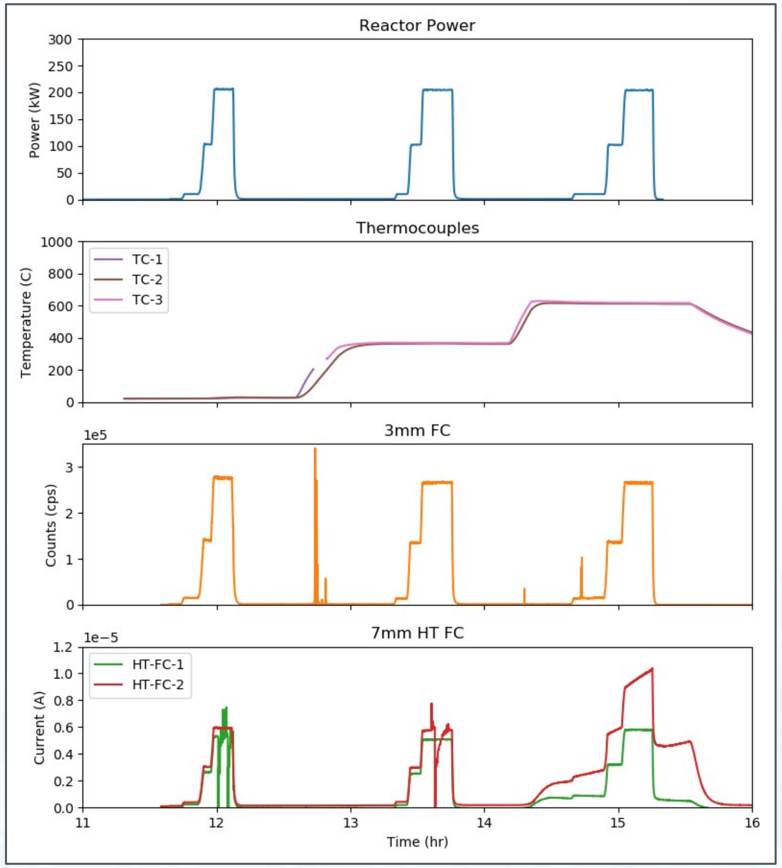
Their design gives them exceptional mechanical and electrical features to facilitate their use. As for instance, the standing wave ration (SWR) is only <17.7 dB and complies with the MIL-T81492 standard. Moreover, the attenuation of this cable remains very low at 0.5 Db/m/GHz up to 20 GHz for an outer diameter of 3 mm.

Thermocoax cable for 3mm FC

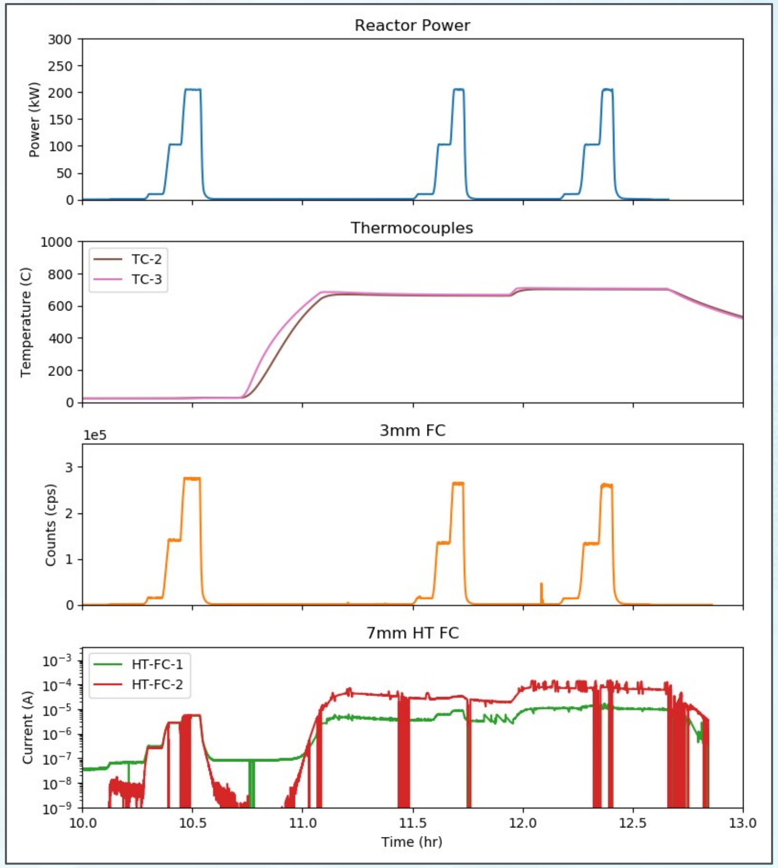


Results and Accomplishments

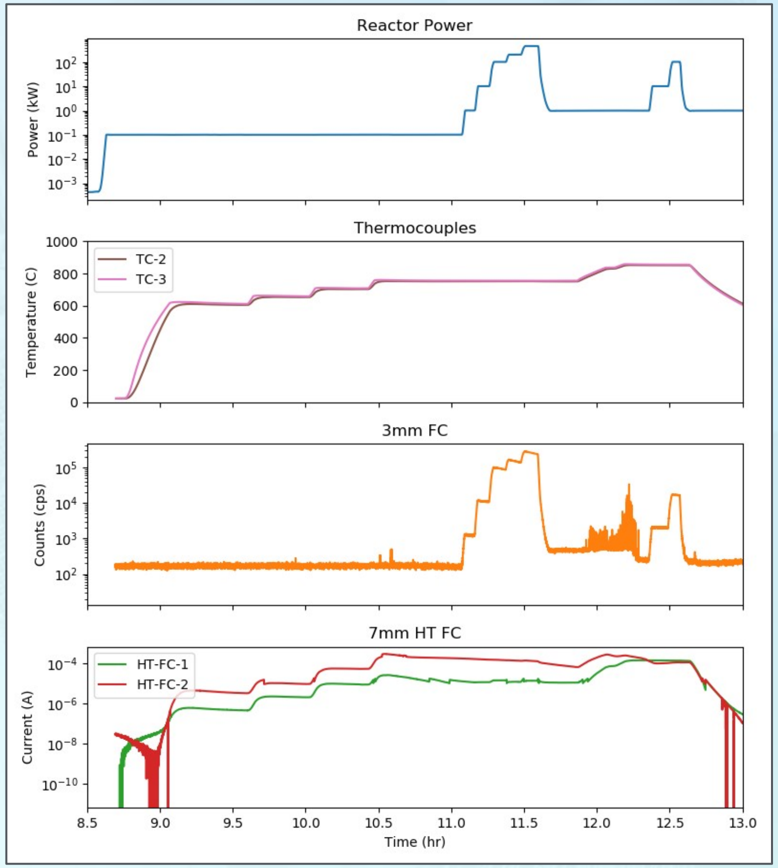
Fission Chamber Results



Day 1 Experiment
Max temp 600C



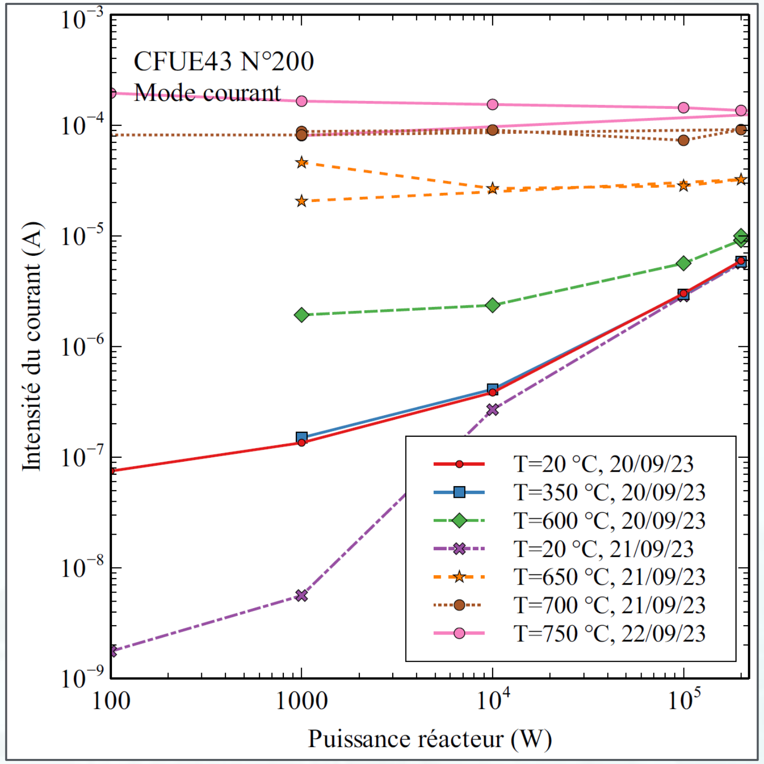
Day 2 Experiment
Max temp 700C



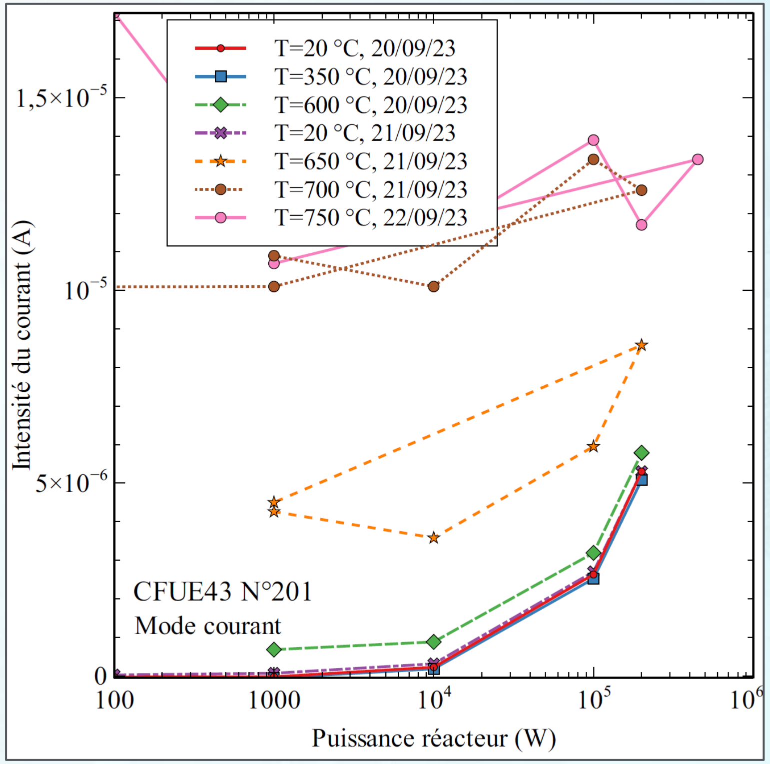
Day 3 Experiment
Max temp 850C

Results and Accomplishments

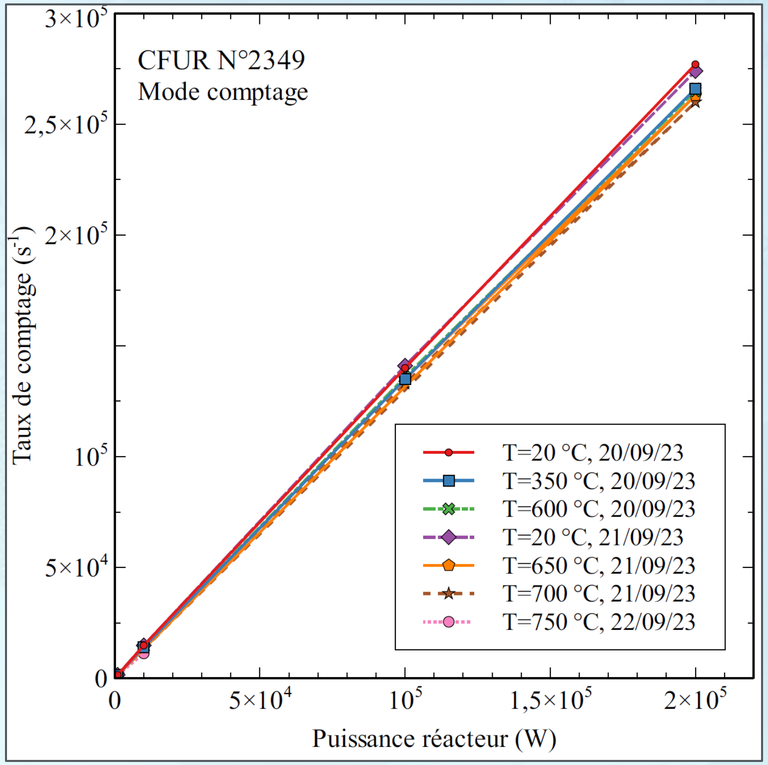
Fission Chamber Results



HT-FC-1 response to temperature



HT-FC-1 response to temperature

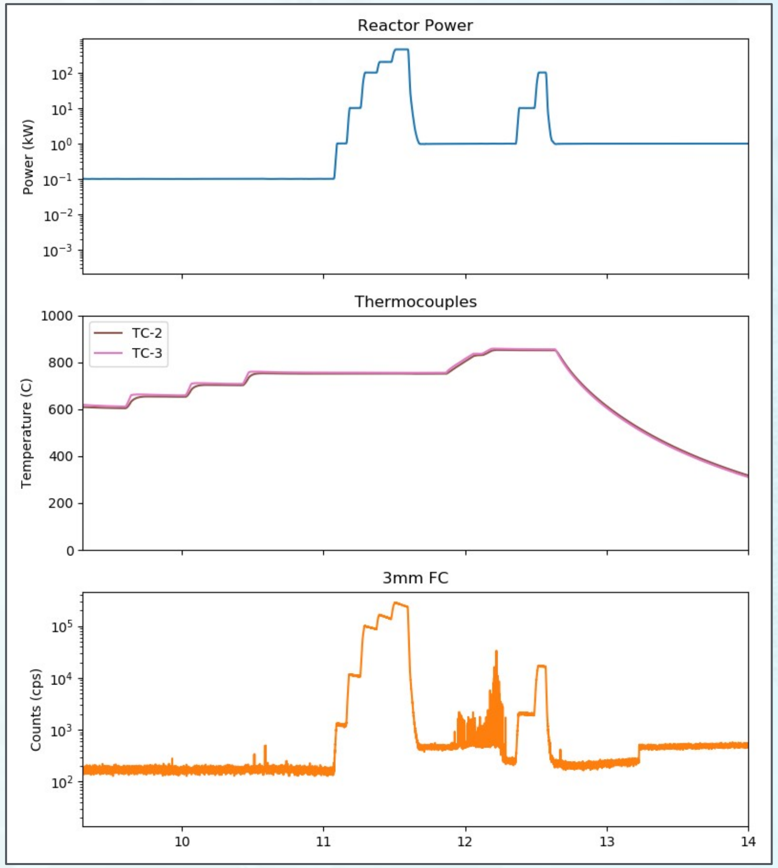


3mm FC response to temperature

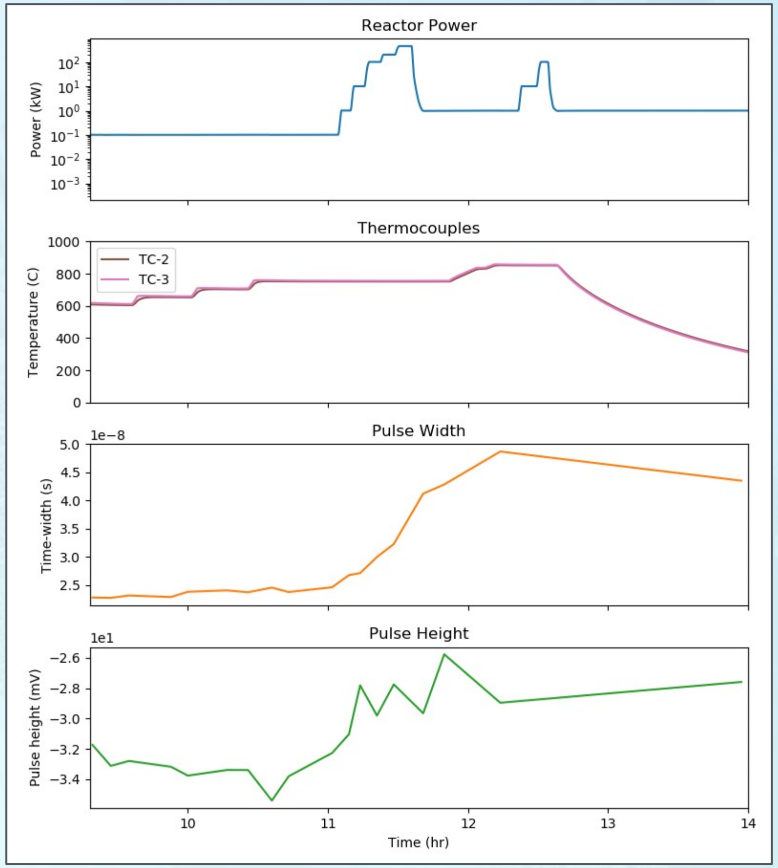
Results and Accomplishments

3mm Fission Chamber Failure Mode

- Failure of the gas-chamber seal
  - Occurs at 750 ℃ near power increase
  - Loss of fill-gas pressure
  - Decrease in count rate over time
  - Increase in average pulse width
  - Decrease in average pulse amplitude
- High voltage decrease from 250V to 150V



3mm fission chamber failure observed



Pulse width and pulse height progression

Concluding Remarks

Overview of Activities

Performed heated irradiation of commercial fission chambers at OSURR for temperature ranges of 600 – 850˚C. This completes the experimental phase of two activities.

- Demonstrated the advantages of pulse mode operation – informed potential fabrication improvements
- Identified drawback of current mode operation at temperature – over saturation of signal from leakage currents
- (11/31/23 Report Due) Report “Irradiation results of commercial and developmental fission chambers at high-temperatures”
- (11/15/23 Slides Due) Document “High-temperature testing of neutron flux sensors at OSURR”

(Ongoing) M3CT-24IN0702012 – Demonstration of temperature compensation techniques for SPNDs operating in high temperature environments

- (01/31/24 Report Due) Report “Testing of temperature compensation techniques for SPNDs operating at high temperatures”

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Thank You