INL/MIS-19-54270-Revision-0

Slides for Performance of Custom-Made Very High Temperature Thermocouples in the Advanced Gas Reactor Experiment AGR-5/6/7 During Irradiation in the Advanced Test Reactor

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June 2019

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operated by Battelle Energy Alliance

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Prepared for the
U.S. Department of Energy

Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Performance of Custom-Made Very High Temperature Thermocouples in the Advanced Gas Reactor Experiment AGR-5/6/7 During Irradiation

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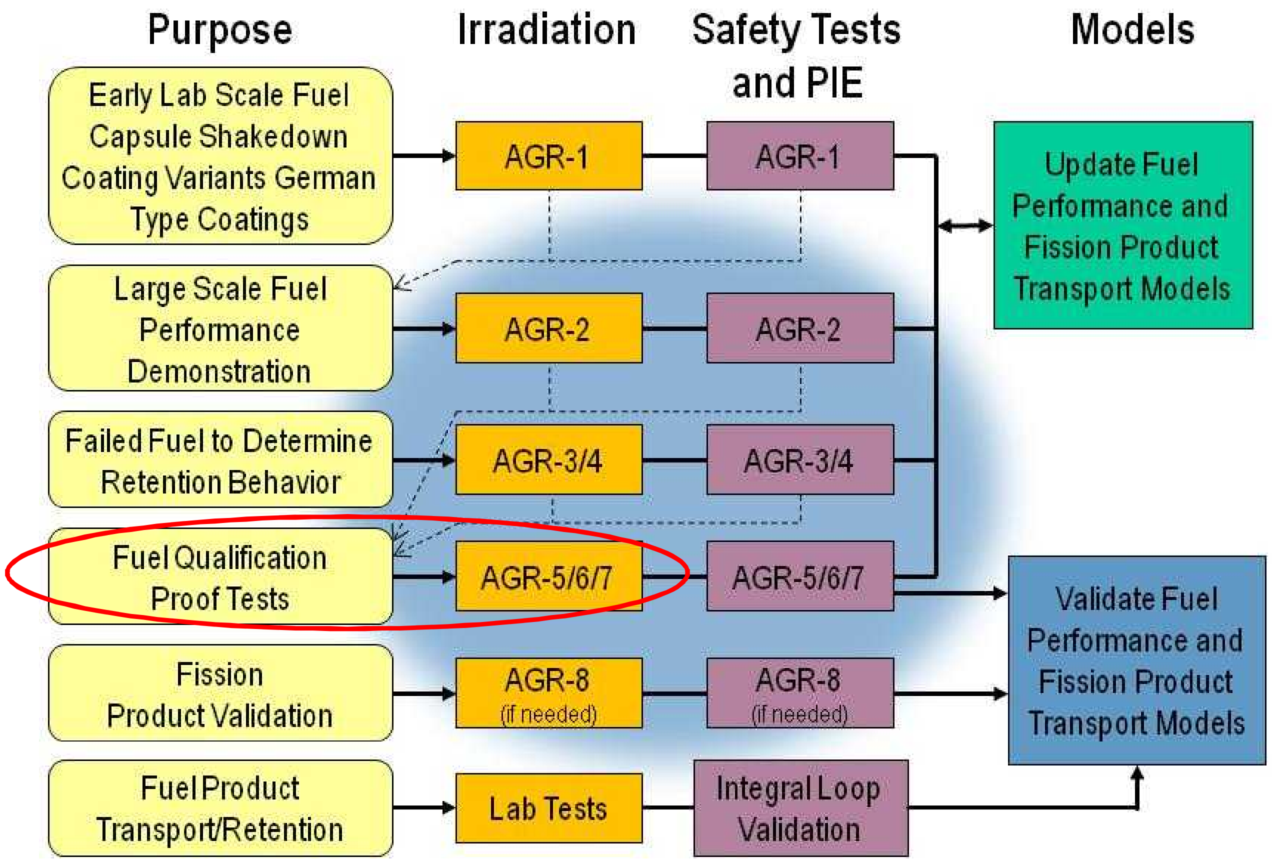
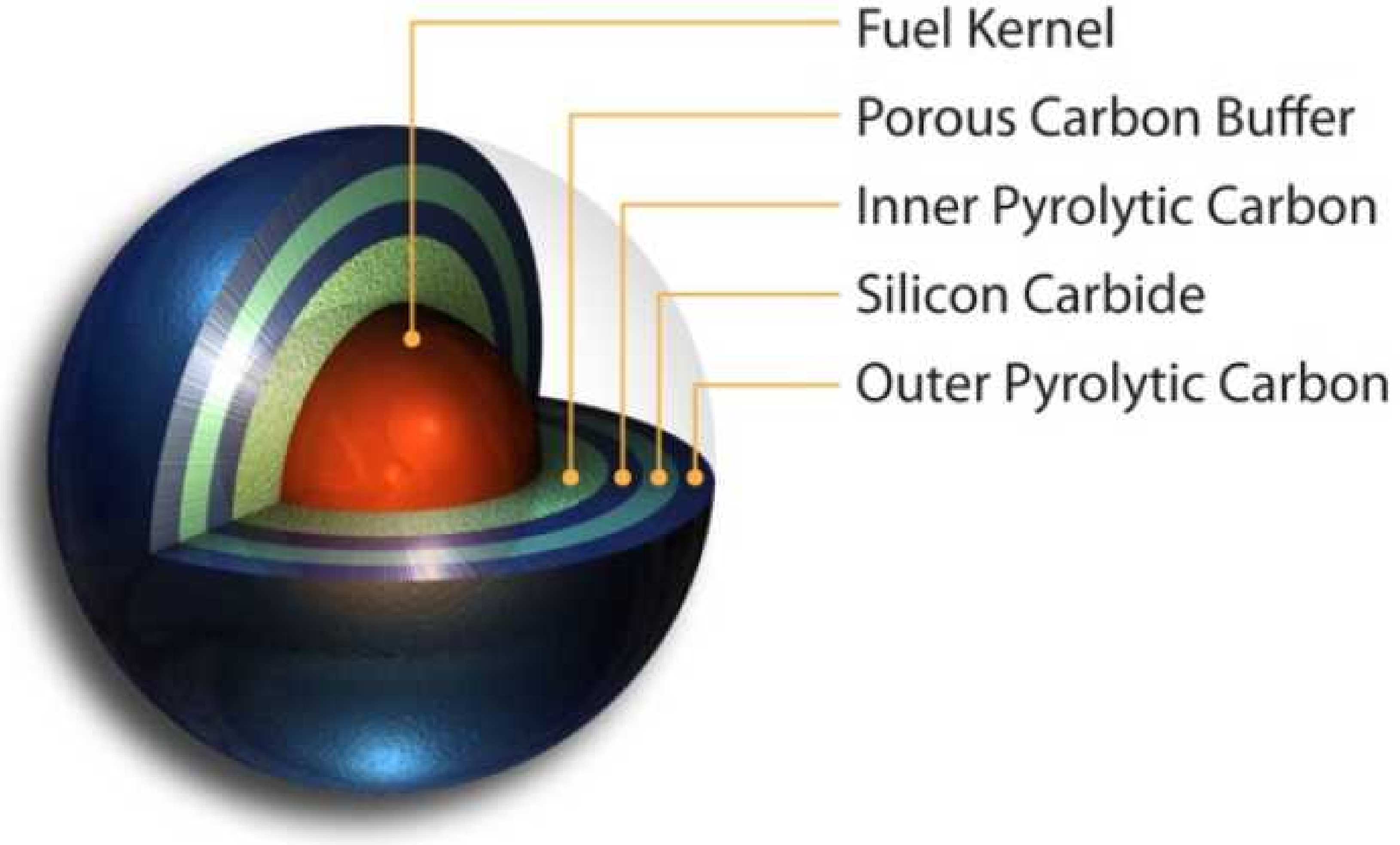
AGR Experiment Overview



- AGR-5/6/7 mission and details
  - Fuel qualification (AGR-5/6) and margin test (AGR-7)
  - Originally envisioned as three separate tests
  - Covers wide range of temperatures and fuel burnup

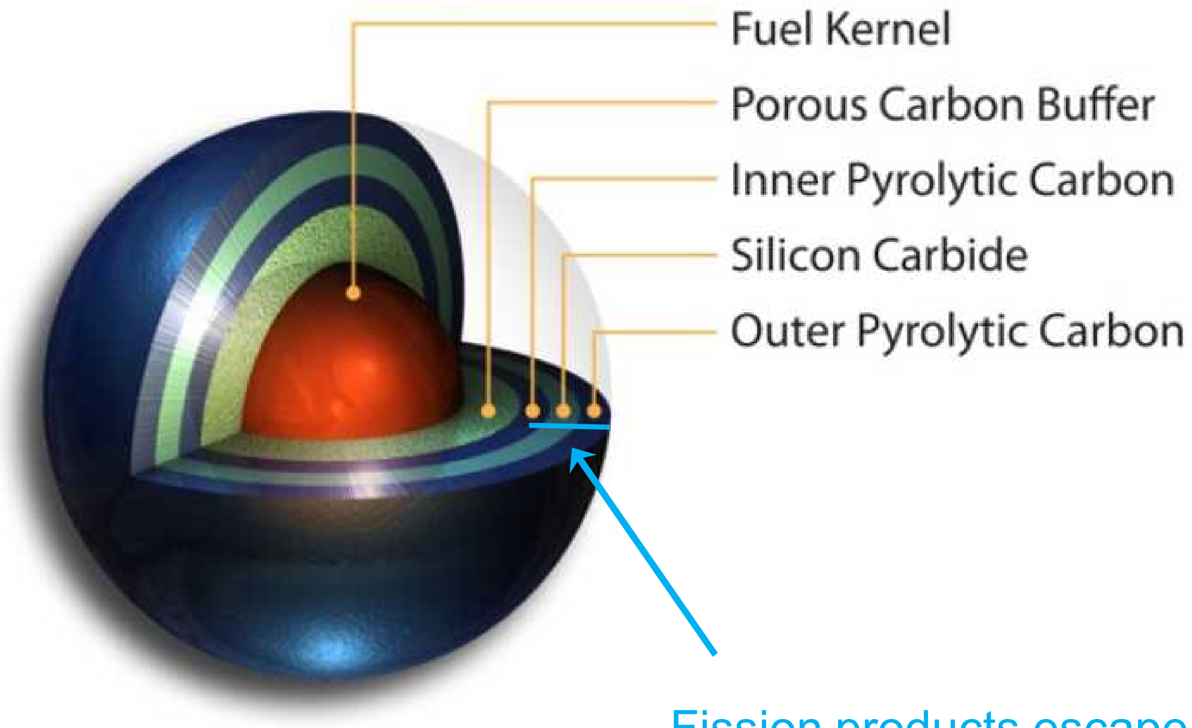
Fuel Particle



Fuel Compact

Particles are combined with matrix and resin material and pressed into compacts

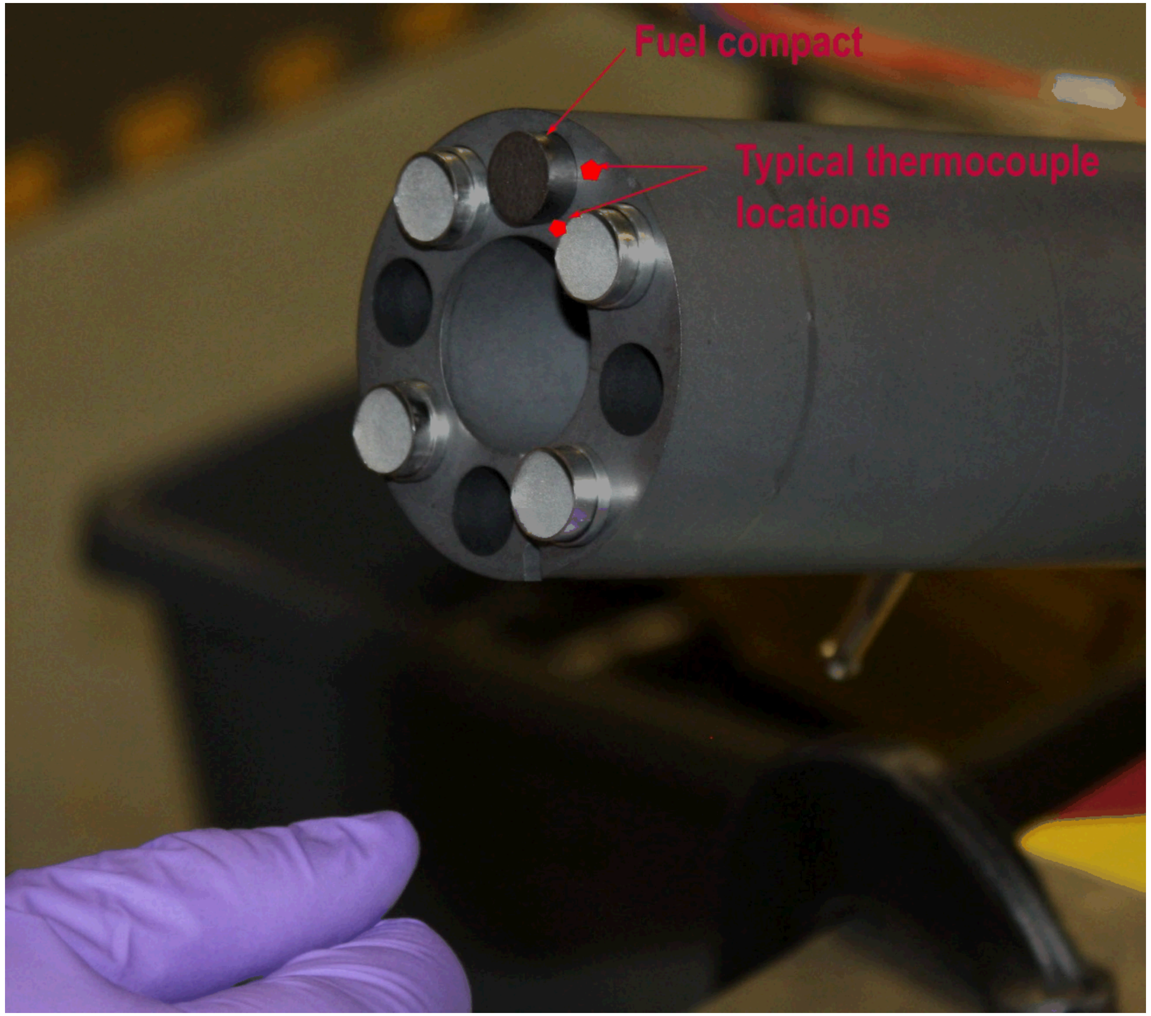
Purpose of AGR-5/6/7 Experiment



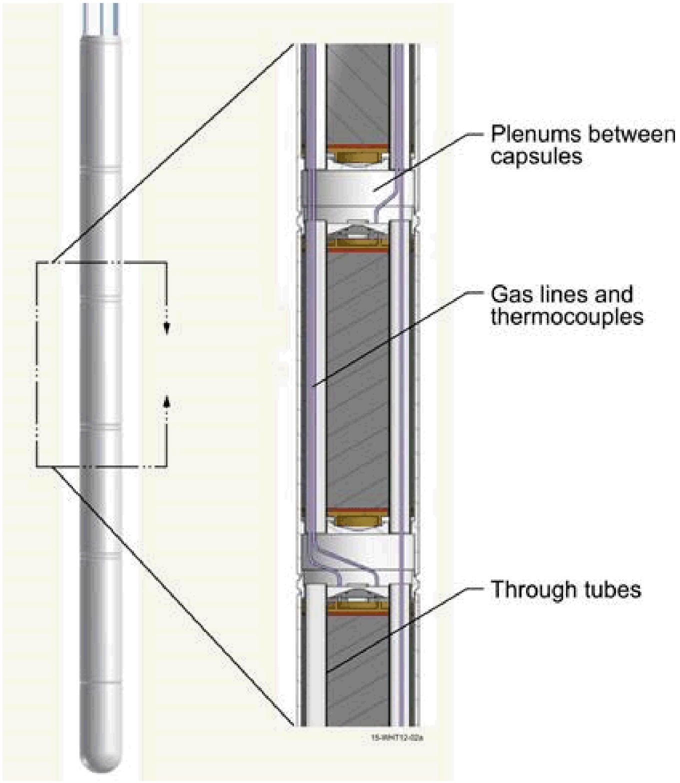
Fission products escape when one or more of these barriers fails

The purpose of the AGR-5/6/7 experiment is to demonstrate fission products are retained when irradiated at reactor operating temperatures and above

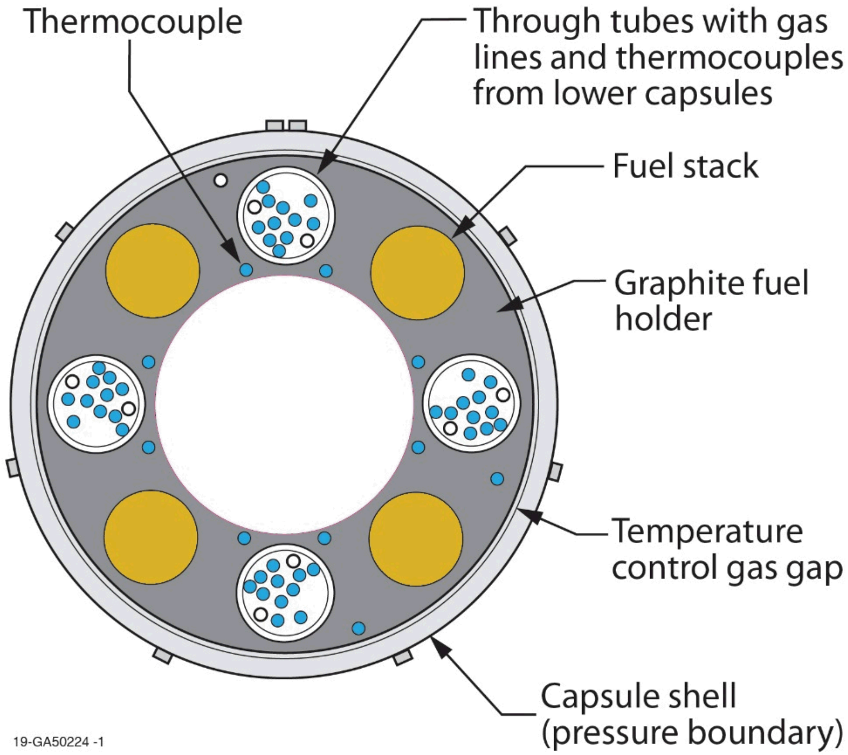
Fuel Compact Inserted in Graphite Holder



AGR-5/6/7 Test Train Design

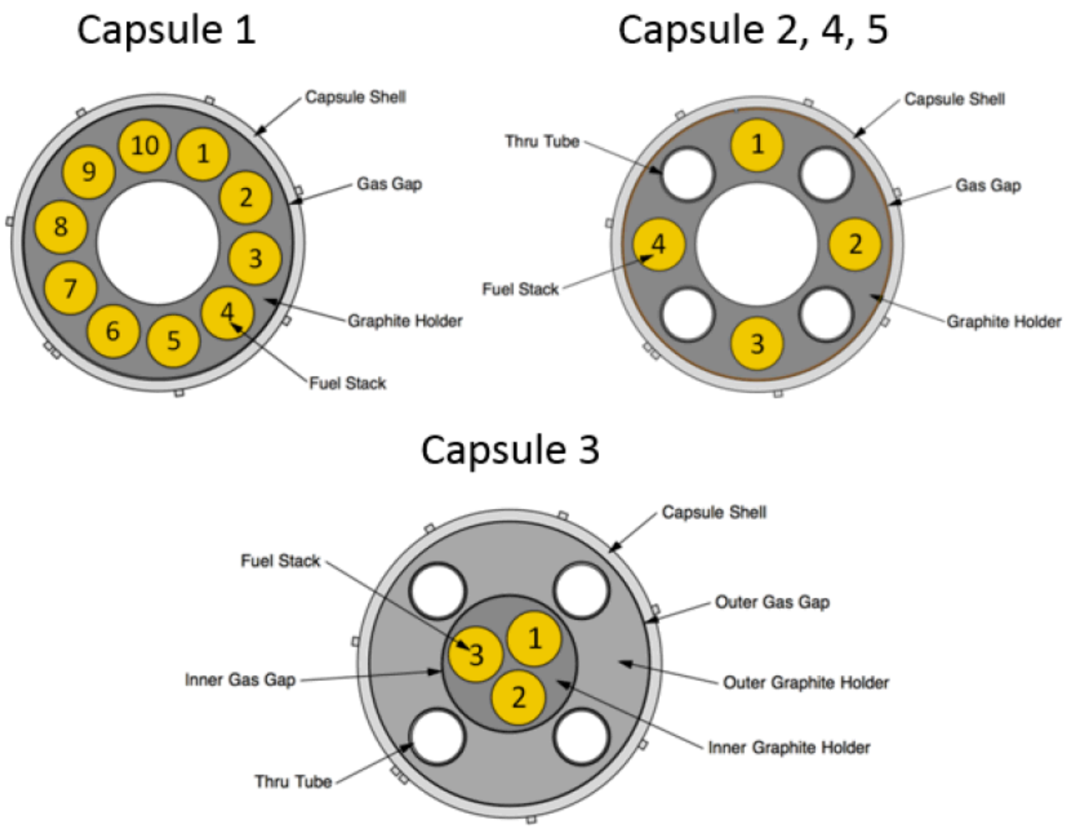


Elevation view of AGR-5/6/7 experiment

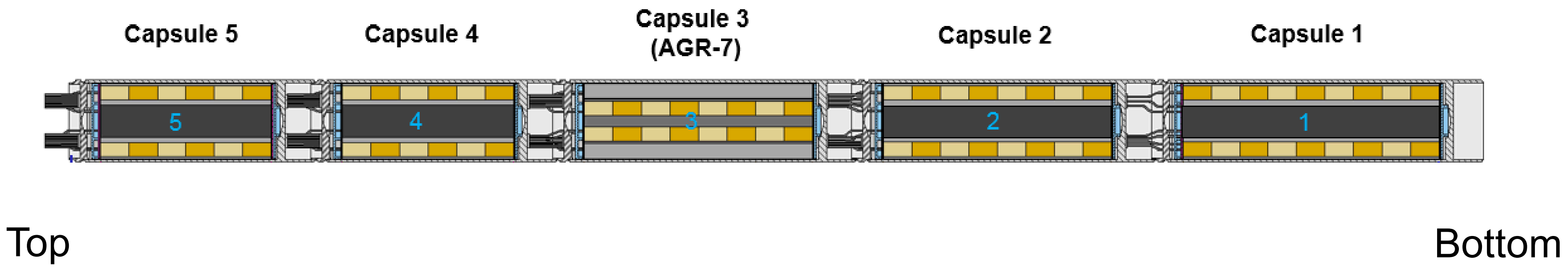


Cross-section view of AGR-5/6/7 experiment

Three Different Capsule Cross Sections



Capsule Layout



It is Difficult to Measure Very High Temperatures in a Reactor Environment

Why?

- Standard base metal thermocouples (Type K and Type N) drift at high temperatures due to metallurgical changes (above 600°C for Type K and above 1050°C for Type N)

- High temperature refractory thermocouples such as Types C, S, B, and R have high cross section alloying elements and are subject to rapid decalibration (drift) because their alloying elements transmute into other elements with different electromotive properties

Measuring High Temperatures in the AGR-5/6/7 Experiment

- The projected temperature measurement range for AGR-5/6/7 thermocouples encompasses a range from 600°C to 1450°C. Therefore for the temperatures above 1050°C advanced thermocouple types were needed.
- Recognizing the limitations of existing thermometry to measure such high temperatures, the sponsor of the AGR-5/6/7 test supported a development and testing program for thermocouples capable of low-drift operation at temperatures above 1100°C for approximately 10,000 hrs.

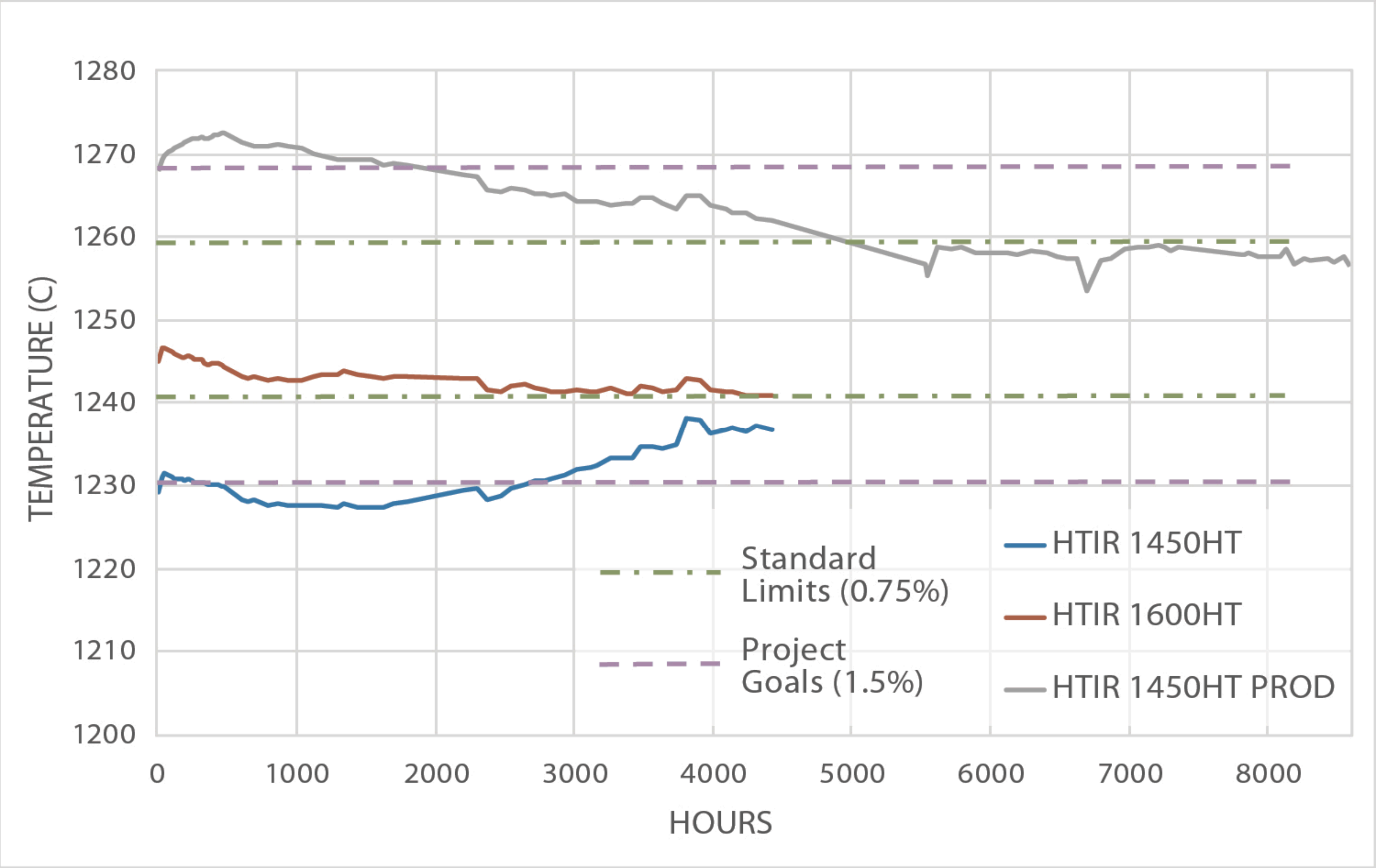
Development and Testing Program

- A four-year instrumentation development and testing effort (2015–2018) was conducted in association with the AGR-5/6/7 experiment program. This was a two pronged approach involving two very different thermocouple systems.
- First, a Mo/Nb based thermocouple system, called High Temperature Irradiation Resistant (HTIR)-TC, which has been under development at Idaho National Laboratory since circa 2004 was further developed. The promise of this thermocouple for high-temperature reactor experiments is based on the high melting temperatures of Mo and Nb and the low thermal-neutron absorption cross sections of both of these elements .

HTIR-TC Details

- Thermoelements – pure Mo or Nb are not used. Instead,
  - Molybdenum alloyed with La (0.5–1.0%)
  - Niobium alloyed with P ≤0.1%, Ta ≤0.3%
- Insulation – Alumina or Hafnia. Alumina was used to avoid activation problems in the reactor
- Sheath material - pure Nb was used for the AGR-5/6/7 thermocouples with heat treatment at 1450°C

HTIR-TC Long Term Drift Test (furnace at 1250°C)

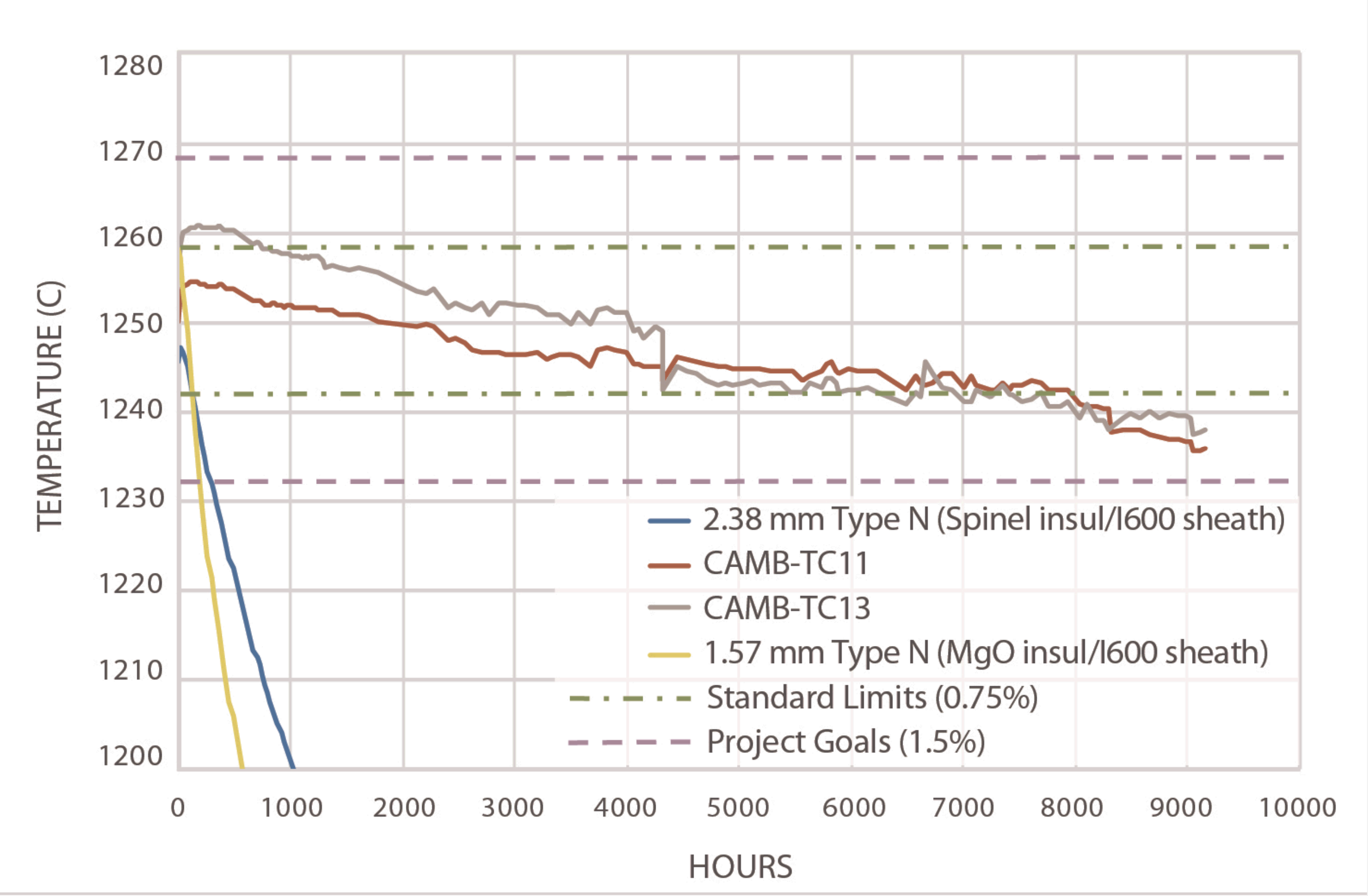


Cambridge Type N Thermocouples

- This thermocouple type incorporates a special proprietary sheath that limits migration of elements from the sheath to the thermoelments when operated at temperatures >1100°C.

- INL has conducted long term drift tests on this thermocouple type since 2014. At 1250°C, Cambridge Type N drifts at about 2.5°C per 1000 hrs compared to standard Type N which drift at about 50°C per 1000 hrs.

Cambridge Type N Long Term Drift Test Compared to Standard Type N (1250°C furnace temperature)



Irradiation Testing Results – First Four Reactor Cycles

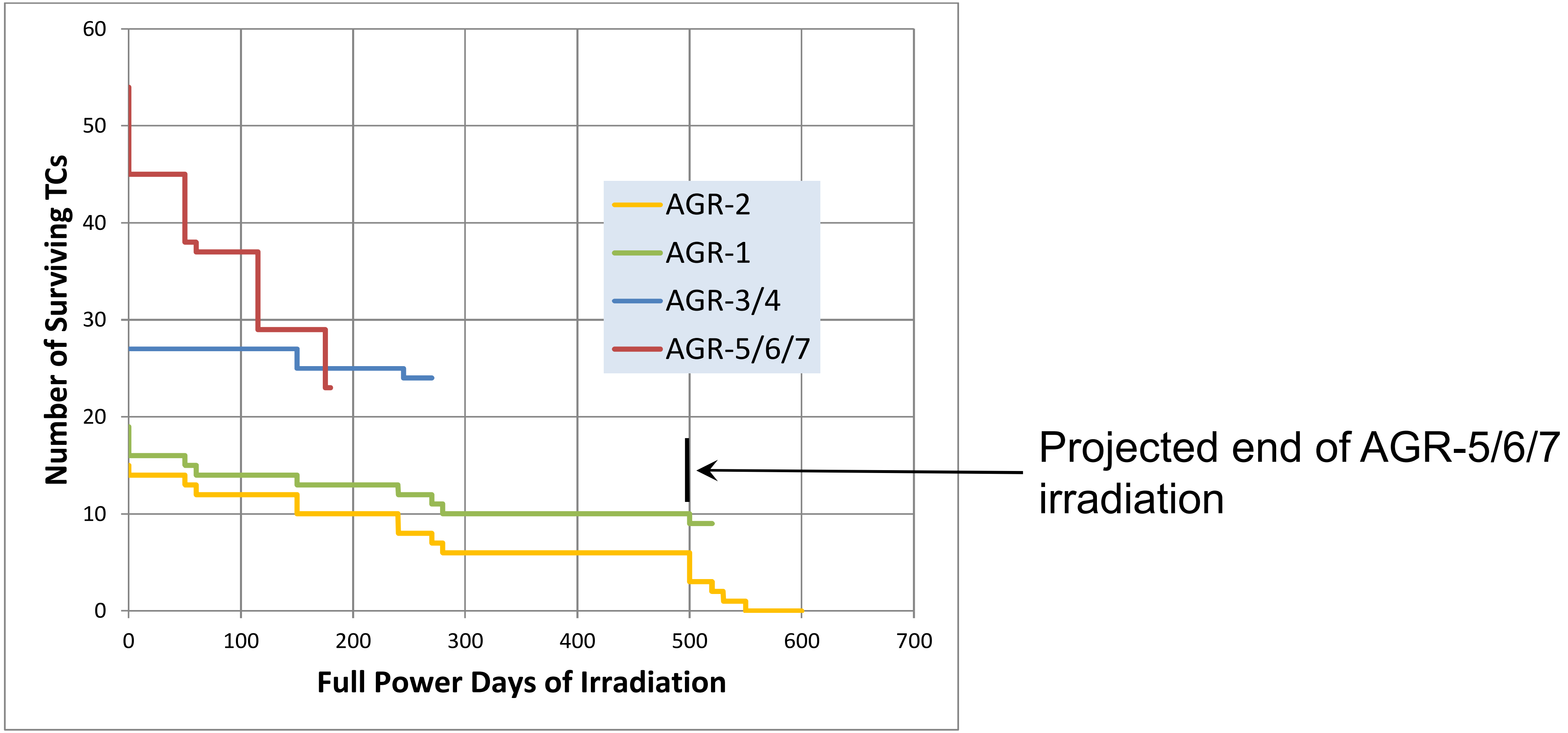
In-Pile Testing Results – Failure rate

SURVIVING THERMOCOUPLES BY CAPSULE AND IRRADIATION CYCLE

Survivors by Capsule/Type		End of Assem	End of Install	End of 162B	End of 163A	End of 164A	End of 164B
Cap 5	STD	4	3	3	3	3	3
Cap 4	STD	5	4	4	4	4	4
Cap 3	STD	4	4	4	4	4	4
	CAMB	7	5	5	5	2	2
	HTIR	4	4	3	3	3	3
Cap 2	STD	8	8	8	8	6	3
Cap 1	STD	1	1	1	0	0	0
	CAMB	7	7	6	6	3	1
	HTIR	9	9	4	4	4	3
Total Surviving		49	45	38	37	29	23

HTIR-TC survived better than Cambridge Type N in the hottest locations

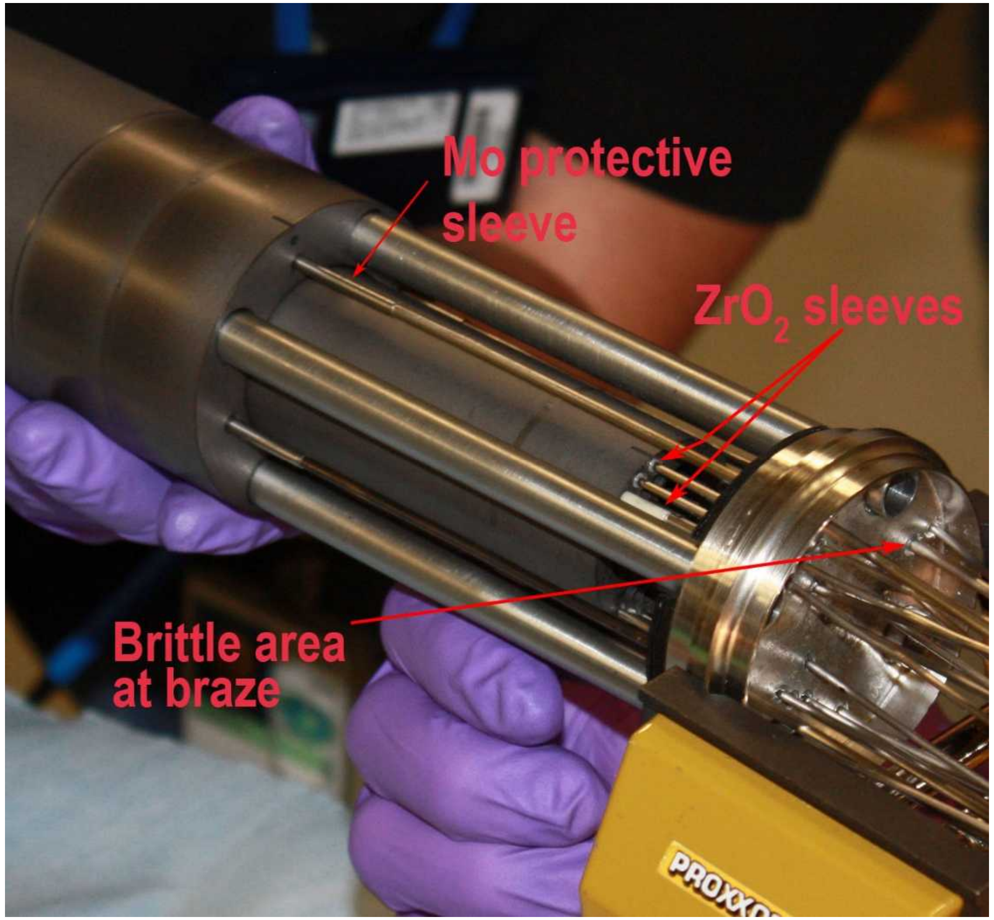
In-Pile Testing Results – Failure Rate Compared to Previous AGR Experiments



Thermocouple failure trends for AGR-1, AGR-2, AGR-3/4, and AGR-5/6/7

One Cause of Open-Circuit Failures

Thermocouples experience considerable thermal expansion between reactor cycles and they may fail at the braze where the sheaths pass through the capsule head

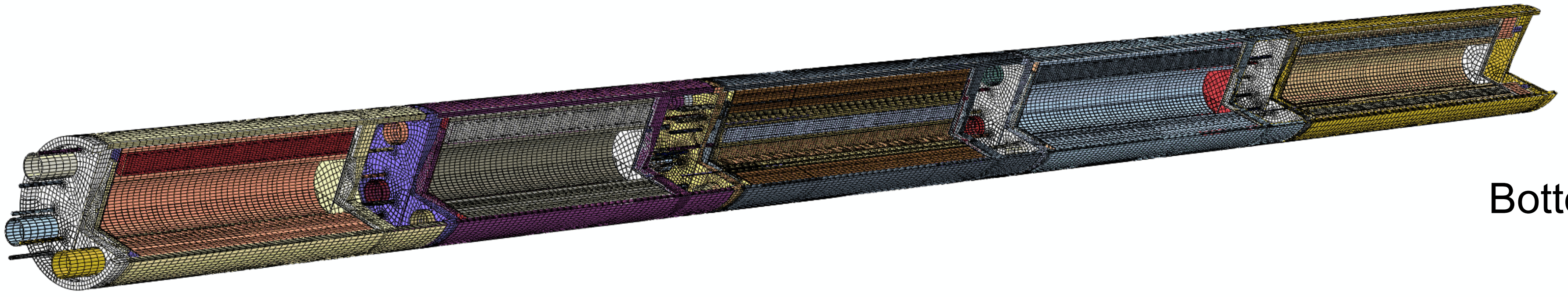


Capsule 3 During Assembly

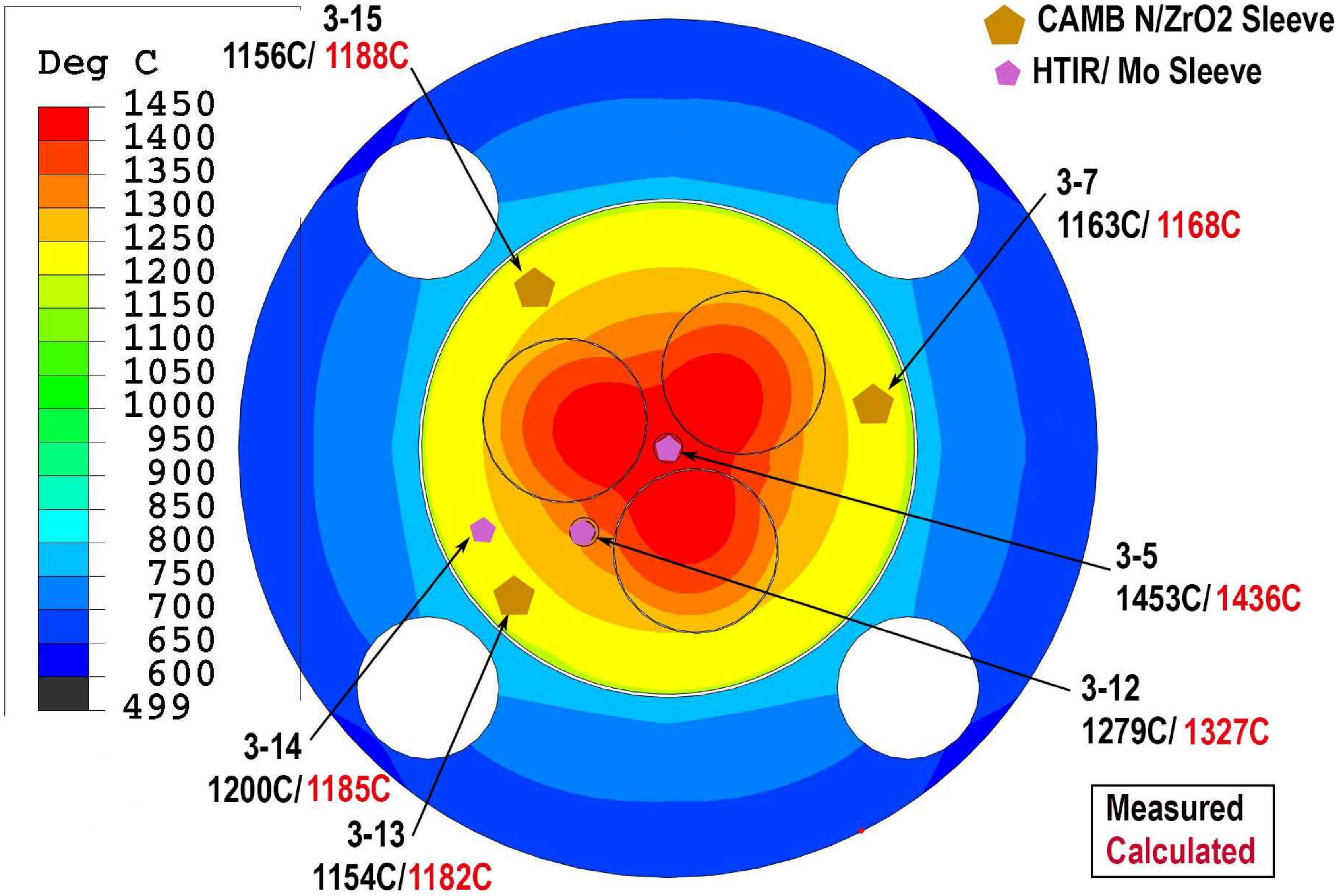
Measured Temperatures Compared to Thermal Model

ABAQUS Finite Element Mesh

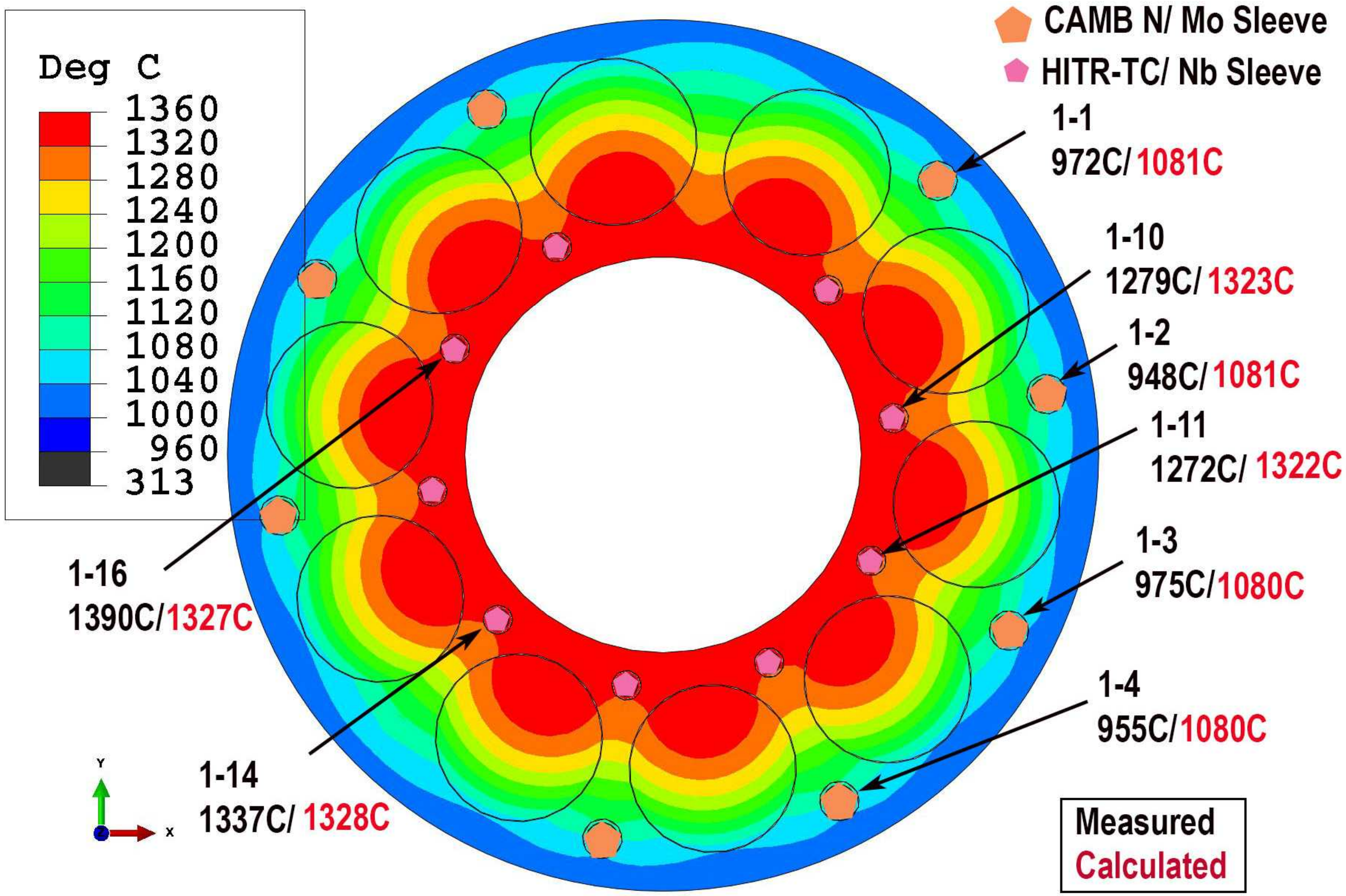
- 1,200,000 hexahedral finite element bricks



Capsule 3 Thermocouples Measured vs Calculated at Startup

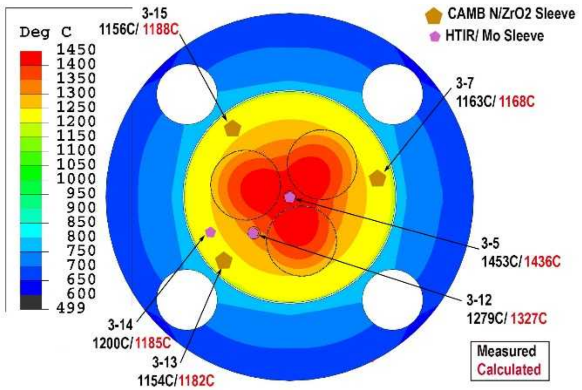


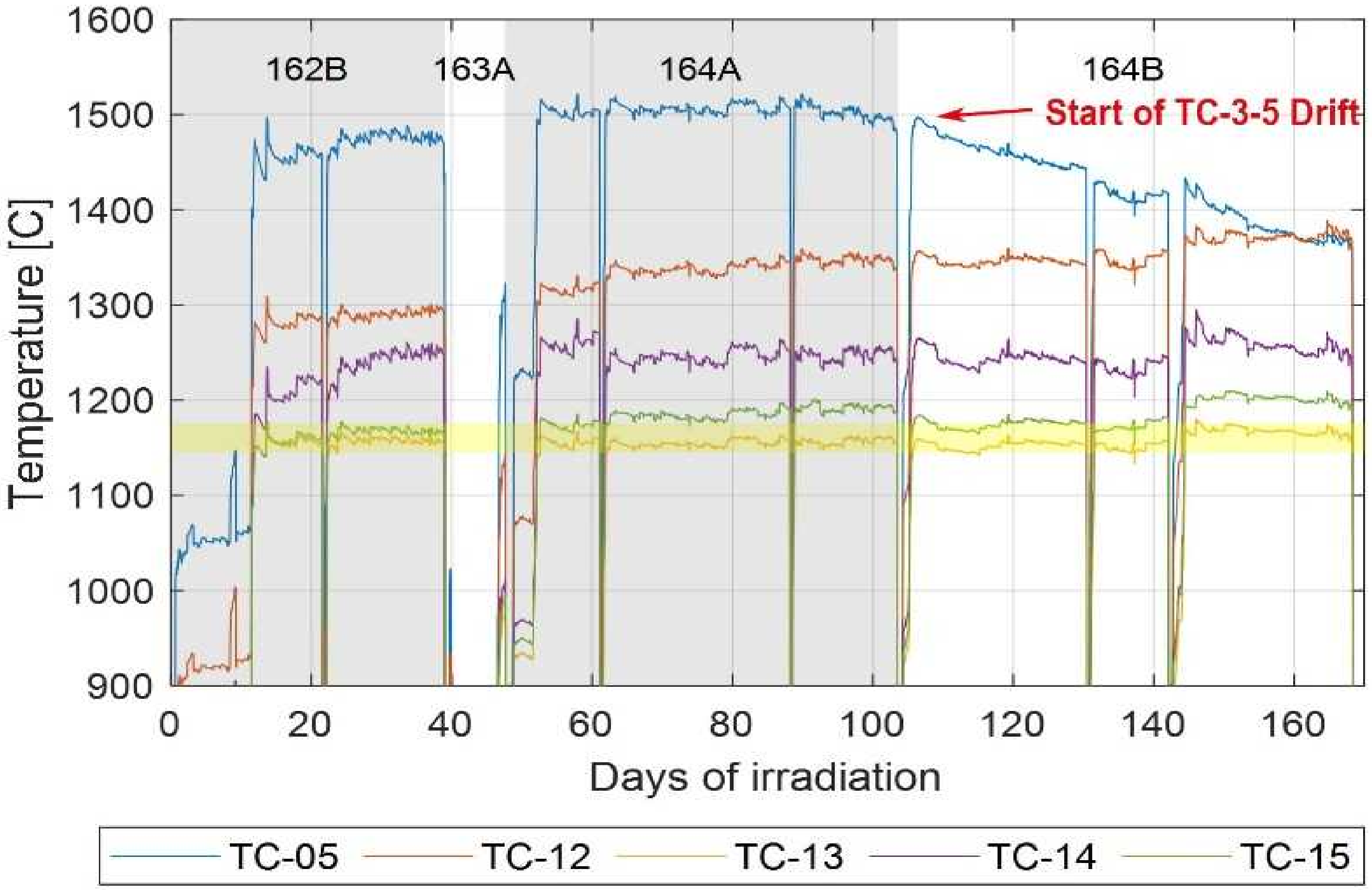
Capsule 1 Thermocouples Measured vs Calculated at Startup



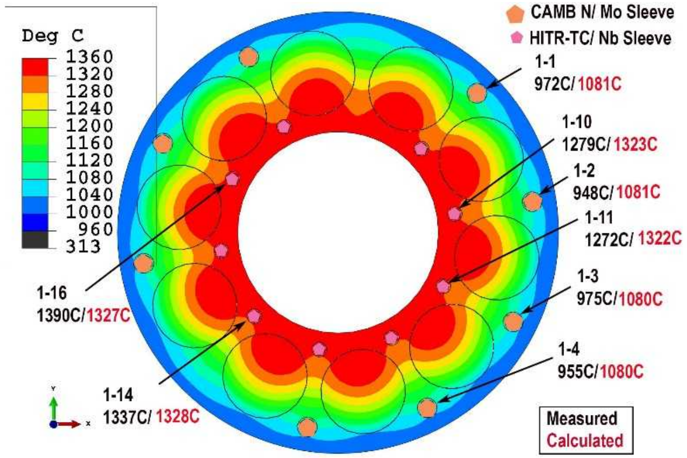
Capsule 3 Selected Thermocouple Trends

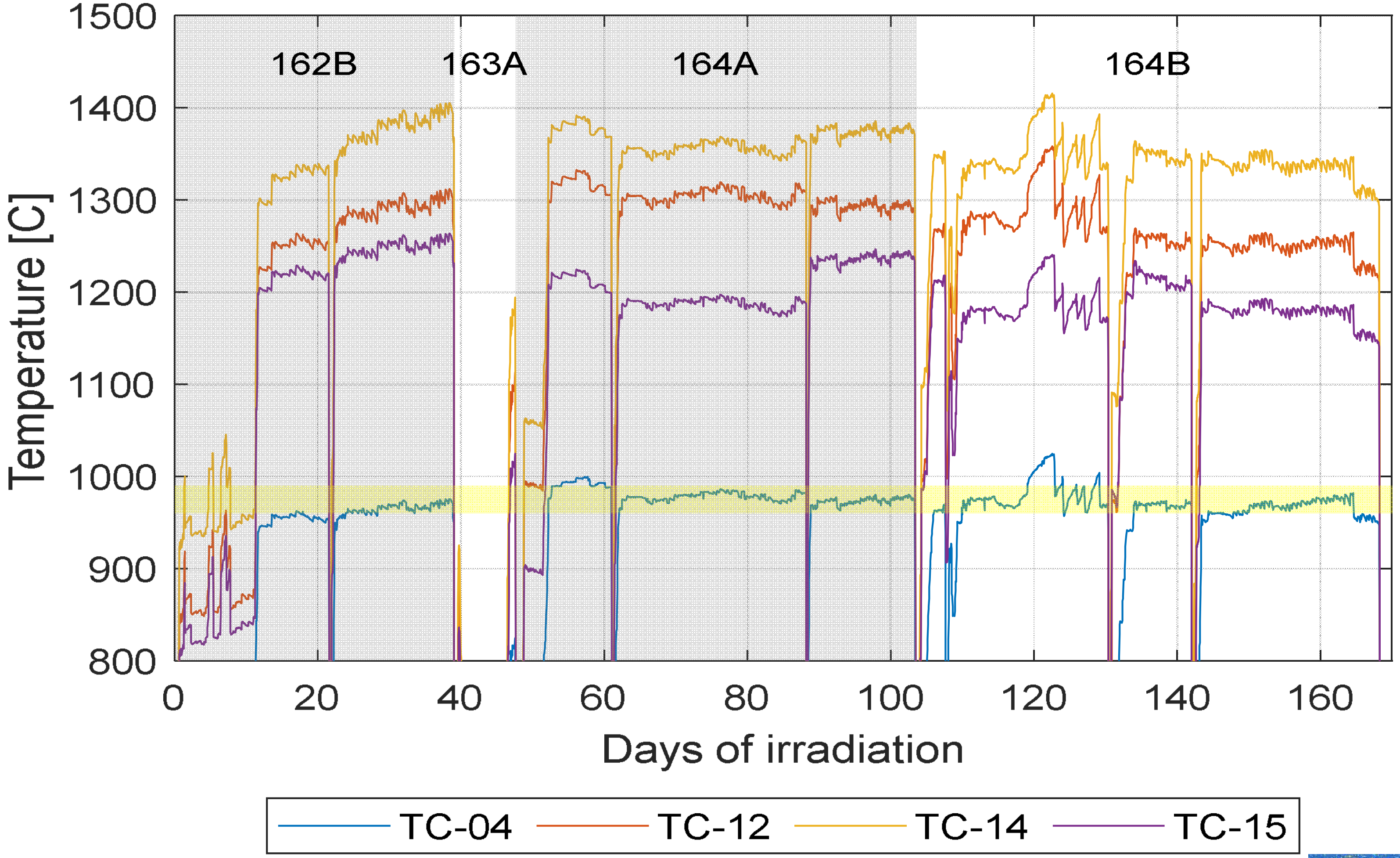
TC-05 operated stably at about 1450°C -1500°C for 85 days – we believe this is highest "drift free" temperature ever measured by a thermocouple in a high neutron flux environment





Capsule 1 Selected Thermocouple Trends





Conclusions

- Three thermocouple types were incorporated into the AGR-5/6/7 experiment: HTIR-TC, Cambridge Type N, and standard Type N.
- Prior to selecting these thermocouples, a development and testing program was conducted and improvements made to the HTIR-TC design.
- Partly because of the extreme temperatures, the experiment has experienced a relatively high thermocouple failure rate. However, all capsules had at least three surviving thermocouples at the end of four cycles.
- In the high temperature regions, the HTIR-TCs suffered a lower failure rate compared to Cambridge Type N.
- One HTIR-TC operated at 1450–1500°C for 85 days without observable drift, which we believe to be the highest sustained temperature ever recorded in a reactor experiment. Three other HTIR-TCs operated at 1250–1400°C, also without observable drift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Questions?

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