October 13, 2020

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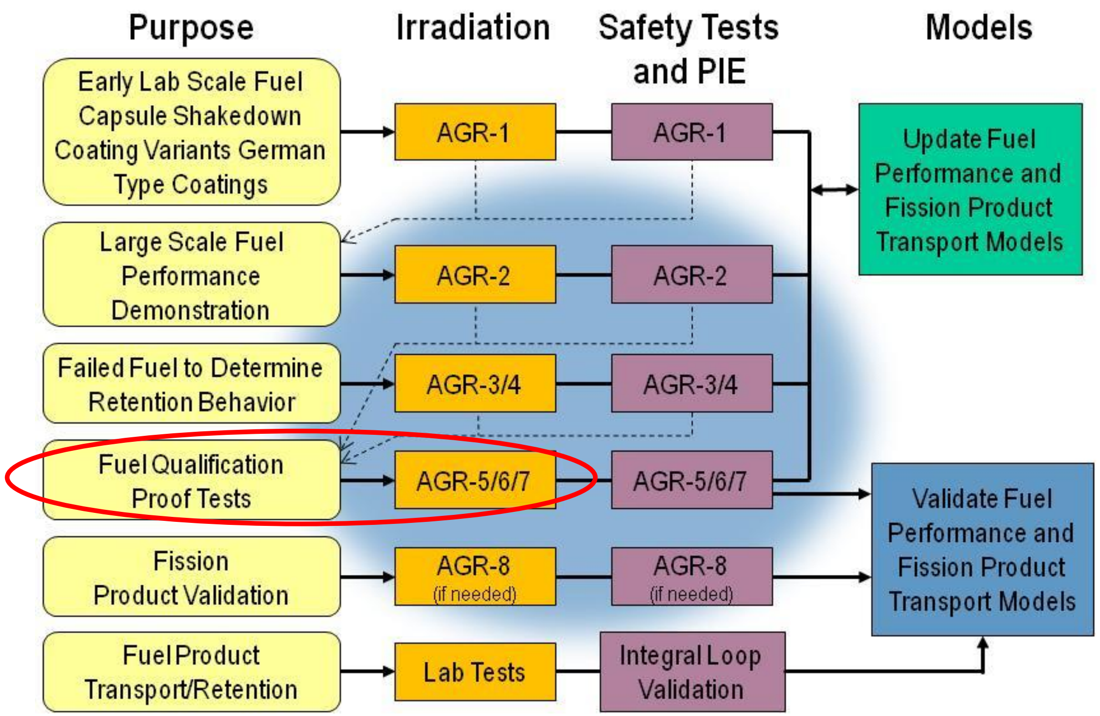
AGR-5/6/7 Overview

Instrumentation for very high-temperature gas cooled fuel experiment

Idaho National Laboratory

AGR Experiment Overview

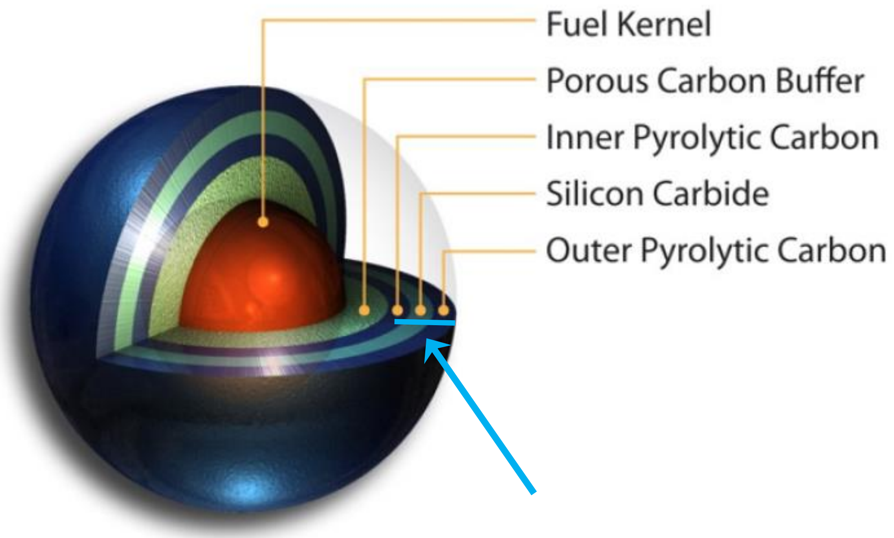
AGR-5/6/7 was irradiated in ATR February 2018 – August 2020



- 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

AGR-5/6/7 was the fourth and final fuel test conducted in the series

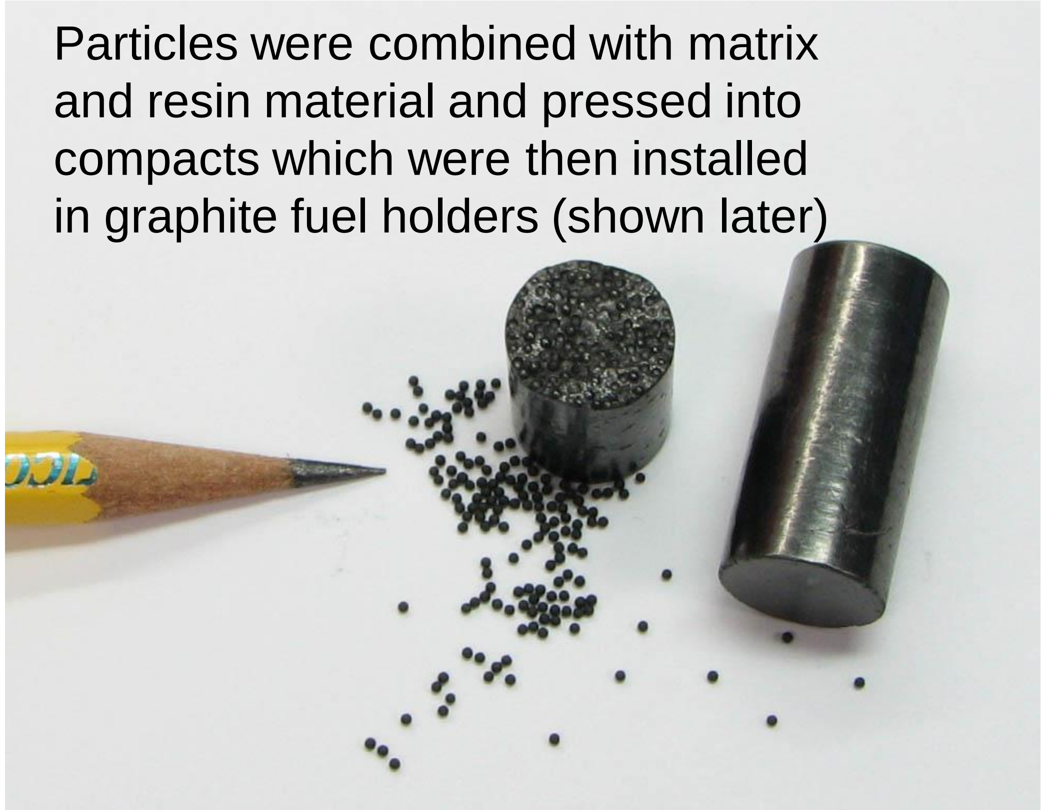
Purpose of AGR-5/6/7 Experiment



Fission products escape when one or more of these barriers fails

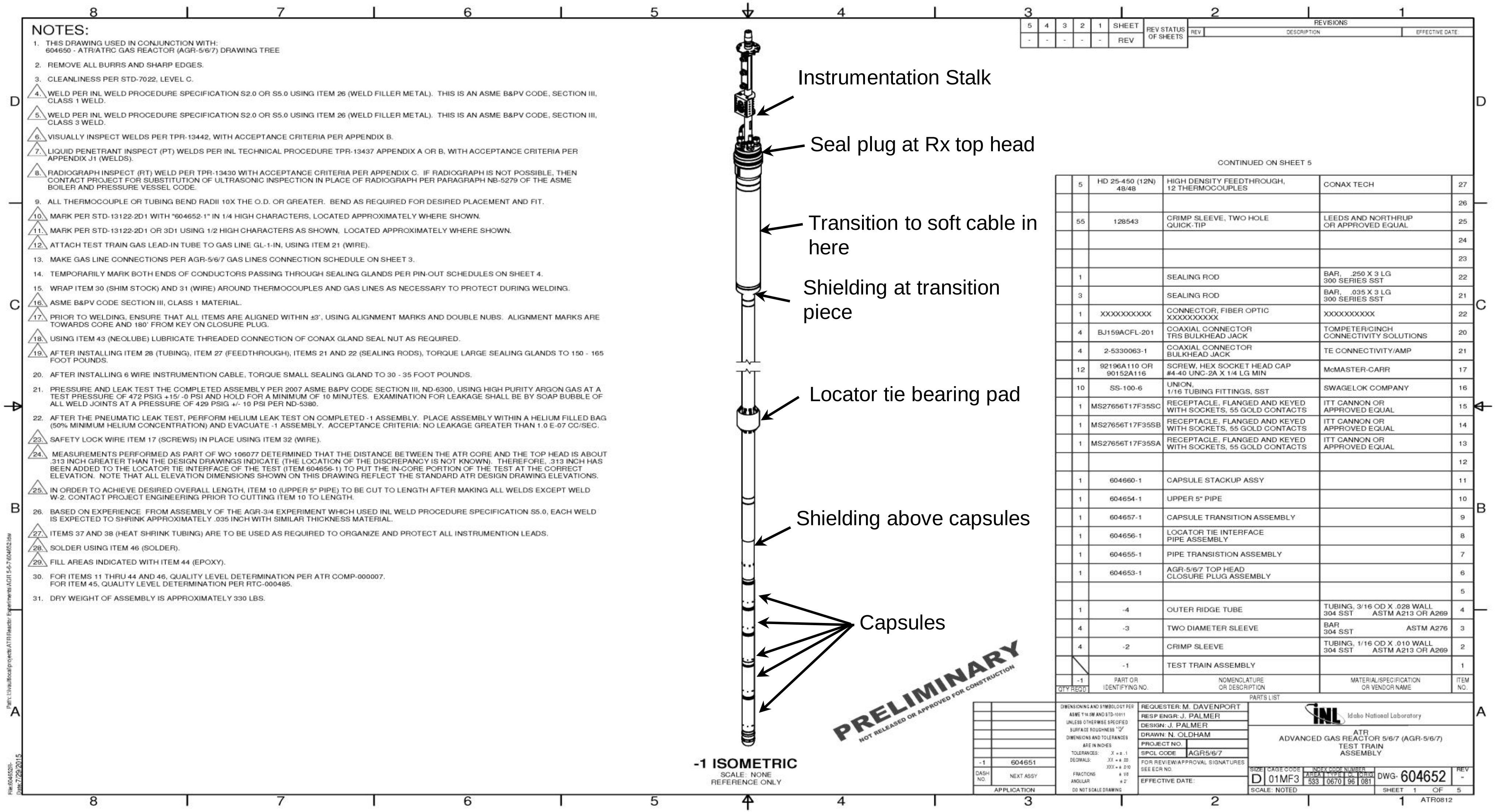
The purpose of the AGR-5/6/7 experiment was to demonstrate fission products are retained within TRISO particles when irradiated at reactor operating temperatures and above

Fuel Compact



Particles were combined with matrix and resin material and pressed into compacts which were then installed in graphite fuel holders (shown later)

Complete Test Train Assembly



Instrumentation Stalk

Seal plug at Rx top head

Transition to soft cable in here

Shielding at transition piece

Locator tie bearing pad

Shielding above capsules

Capsules

NOTES:

1. THIS DRAWING USED IN CONJUNCTION WITH:
   604650 - ATR/ATRC GAS REACTOR (AGR-5/6/7) DRAWING TREE
2. REMOVE ALL BURRS AND SHARP EDGES.
3. CLEANLINESS PER STD-7022, LEVEL C.
4. WELD PER INL WELD PROCEDURE SPECIFICATION S2.0 OR S5.0 USING ITEM 26 (WELD FILLER METAL). THIS IS AN ASME B&PV CODE, SECTION III, CLASS 1 WELD.
5. WELD PER INL WELD PROCEDURE SPECIFICATION S2.0 OR S5.0 USING ITEM 26 (WELD FILLER METAL). THIS IS AN ASME B&PV CODE, SECTION III, CLASS 3 WELD.
6. VISUALLY INSPECT WELDS PER TPR-13442, WITH ACCEPTANCE CRITERIA PER APPENDIX B.
7. LIQUID PENETRANT INSPECT (PT) WELDS PER INL TECHNICAL PROCEDURE TPR-13437 APPENDIX A OR B, WITH ACCEPTANCE CRITERIA PER APPENDIX J1 (WELDS).
8. RADIOGRAPH INSPECT (RT) WELD PER TPR-13430 WITH ACCEPTANCE CRITERIA PER APPENDIX C. IF RADIOGRAPH IS NOT POSSIBLE, THEN CONTACT PROJECT FOR SUBSTITUTION OF ULTRASONIC INSPECTION IN PLACE OF RADIOGRAPH PER PARAGRAPH NB-5279 OF THE ASME BOILER AND PRESSURE VESSEL CODE.
9. ALL THERMOCOUPLE OR TUBING BEND RADII 10X THE O.D. OR GREATER. BEND AS REQUIRED FOR DESIRED PLACEMENT AND FIT.
10. MARK PER STD-13122-2D1 WITH "604652-1" IN 1/4 HIGH CHARACTERS, LOCATED APPROXIMATELY WHERE SHOWN.
11. MARK PER STD-13122-2D1 OR 3D1 USING 1/2 HIGH CHARACTERS AS SHOWN, LOCATED APPROXIMATELY WHERE SHOWN.
12. ATTACH TEST TRAIN GAS LEAD-IN TUBE TO GAS LINE GL-1-IN, USING ITEM 21 (WIRE).
13. MAKE GAS LINE CONNECTIONS PER AGR-5/6/7 GAS LINES CONNECTION SCHEDULE ON SHEET 3.
14. TEMPORARILY MARK BOTH ENDS OF CONDUCTORS PASSING THROUGH SEALING GLANDS PER PIN-OUT SCHEDULES ON SHEET 4.
15. WRAP ITEM 30 (SHIM STOCK) AND 31 (WIRE) AROUND THERMOCOUPLES AND GAS LINES AS NECESSARY TO PROTECT DURING WELDING.
16. ASME B&PV CODE SECTION III, CLASS 1 MATERIAL.
17. PRIOR TO WELDING, ENSURE THAT ALL ITEMS ARE ALIGNED WITHIN ±3°, USING ALIGNMENT MARKS AND DOUBLE NUBS. ALIGNMENT MARKS ARE TOWARDS CORE AND 180° FROM KEY ON CLOSURE PLUG.
18. USING ITEM 43 (NEOLUBE) LUBRICATE THREADED CONNECTION OF CONAX GLAND SEAL NUT AS REQUIRED.
19. AFTER INSTALLING ITEM 28 (TUBING), ITEM 27 (FEEDTHROUGH), ITEMS 21 AND 22 (SEALING RODS), TORQUE LARGE SEALING GLANDS TO 150 - 165 FOOT POUNDS.
20. AFTER INSTALLING 6 WIRE INSTRUMENTION CABLE, TORQUE SMALL SEALING GLAND TO 30 - 35 FOOT POUNDS.
21. PRESSURE AND LEAK TEST THE COMPLETED ASSEMBLY PER 2007 ASME B&PV CODE SECTION III, ND-6300, USING HIGH PURITY ARGON GAS AT A TEST PRESSURE OF 472 PSIG +15/ -0 PSI AND HOLD FOR A MINIMUM OF 10 MINUTES. EXAMINATION FOR LEAKAGE SHALL BE BY SOAP BUBBLE OF ALL WELD JOINTS AT A PRESSURE OF 429 PSIG +/- 10 PSI PER ND-5380.
22. AFTER THE PNEUMATIC LEAK TEST, PERFORM HELIUM LEAK TEST ON COMPLETED -1 ASSEMBLY. PLACE ASSEMBLY WITHIN A HELIUM FILLED BAG (50% MINIMUM HELIUM CONCENTRATION) AND EVACUATE -1 ASSEMBLY. ACCEPTANCE CRITERIA: NO LEAKAGE GREATER THAN 1.0 E-07 CC/SEC.
23. SAFETY LOCK WIRE ITEM 17 (SCREWS) IN PLACE USING ITEM 32 (WIRE).
24. MEASUREMENTS PERFORMED AS PART OF WO 106077 DETERMINED THAT THE DISTANCE BETWEEN THE ATR CORE AND THE TOP HEAD IS ABOUT .313 INCH GREATER THAN THE DESIGN DRAWINGS INDICATE (THE LOCATION OF THE DISCREPANCY IS NOT KNOWN). THEREFORE, .313 INCH HAS BEEN ADDED TO THE LOCATOR TIE INTERFACE OF THE TEST (ITEM 604656-1) TO PUT THE IN-CORE PORTION OF THE TEST AT THE CORRECT ELEVATION. NOTE THAT ALL ELEVATION DIMENSIONS SHOWN ON THIS DRAWING REFLECT THE STANDARD ATR DESIGN DRAWING ELEVATIONS.
25. IN ORDER TO ACHIEVE DESIRED OVERALL LENGTH, ITEM 10 (UPPER 5" PIPE) TO BE CUT TO LENGTH AFTER MAKING ALL WELDS EXCEPT WELD W-2. CONTACT PROJECT ENGINEERING PRIOR TO CUTTING ITEM 10 TO LENGTH.
26. BASED ON EXPERIENCE FROM ASSEMBLY OF THE AGR-3/4 EXPERIMENT WHICH USED INL WELD PROCEDURE SPECIFICATION S5.0, EACH WELD IS EXPECTED TO SHRINK APPROXIMATELY .035 INCH WITH SIMILAR THICKNESS MATERIAL.
27. ITEMS 37 AND 38 (HEAT SHRINK TUBING) ARE TO BE USED AS REQUIRED TO ORGANIZE AND PROTECT ALL INSTRUMENTION LEADS.
28. SOLDER USING ITEM 46 (SOLDER).
29. FILL AREAS INDICATED WITH ITEM 44 (EPOXY).
30. FOR ITEMS 11 THRU 44 AND 46, QUALITY LEVEL DETERMINATION PER ATR COMP-000007.
    FOR ITEM 45, QUALITY LEVEL DETERMINATION PER RTC-000485.
31. DRY WEIGHT OF ASSEMBLY IS APPROXIMATELY 330 LBS.

SHEET	5	4	3	2	1	REV STATUS OF SHEETS
REV	-	-	-	-	-	

REVISIONS

REV	DESCRIPTION	EFFECTIVE DATE:

-1 ISOMETRIC
SCALE: NONE
REFERENCE ONLY

PRELIMINARY
NOT RELEASED OR APPROVED FOR CONSTRUCTION

CONTINUED ON SHEET 5

QTY REQD	-1	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION OR VENDOR NAME	ITEM NO.
	5	HD 25-450 (12N) 48/48	HIGH DENSITY FEEDTHROUGH, 12 THERMOCOUPLES	CONAX TECH	27
					26
	55	128543	CRIMP SLEEVE, TWO HOLE QUICK-TIP	LEEDS AND NORTHRUP OR APPROVED EQUAL	25
					24
					23
	1		SEALING ROD	BAR, .250 X 3 LG 300 SERIES SST	22
	3		SEALING ROD	BAR, .035 X 3 LG 300 SERIES SST	21
	1	XXXXXXXXXX	CONNECTOR, FIBER OPTIC XXXXXXXXXX	XXXXXXXXXX	22
	4	BJ159ACFL-201	COAXIAL CONNECTOR TRS BULKHEAD JACK	TOMPETER/CINCH CONNECTIVITY SOLUTIONS	20
	4	2-5330063-1	COAXIAL CONNECTOR BULKHEAD JACK	TE CONNECTIVITY/AMP	21
	12	92196A110 OR 90152A116	SCREW, HEX SOCKET HEAD CAP #4-40 UNC-2A X 1/4 LG MIN	McMASTER-CARR	17
	10	SS-100-6	UNION, 1/16 TUBING FITTINGS, SST	SWAGELOK COMPANY	16
	1	MS27656T17F35SC	RECEPTACLE, FLANGED AND KEYED WITH SOCKETS, 55 GOLD CONTACTS	ITT CANNON OR APPROVED EQUAL	15
	1	MS27656T17F35SB	RECEPTACLE, FLANGED AND KEYED WITH SOCKETS, 55 GOLD CONTACTS	ITT CANNON OR APPROVED EQUAL	14
	1	MS27656T17F35SA	RECEPTACLE, FLANGED AND KEYED WITH SOCKETS, 55 GOLD CONTACTS	ITT CANNON OR APPROVED EQUAL	13
					12
	1	604660-1	CAPSULE STACKUP ASSY		11
	1	604654-1	UPPER 5" PIPE		10
	1	604657-1	CAPSULE TRANSITION ASSEMBLY		9
	1	604656-1	LOCATOR TIE INTERFACE PIPE ASSEMBLY		8
	1	604655-1	PIPE TRANSISTION ASSEMBLY		7
	1	604653-1	AGR-5/6/7 TOP HEAD CLOSURE PLUG ASSEMBLY		6
					5
	1	-4	OUTER RIDGE TUBE	TUBING, 3/16 OD X .028 WALL 304 SST ASTM A213 OR A269	4
	4	-3	TWO DIAMETER SLEEVE	BAR 304 SST ASTM A276	3
	4	-2	CRIMP SLEEVE	TUBING, 1/16 OD X .010 WALL 304 SST ASTM A213 OR A269	2
		-1	TEST TRAIN ASSEMBLY		1

PARTS LIST

DASH NO.	NEXT ASSY
-1	604651

APPLICATION

DIMENSIONING AND SYMBOLOGY PER ASME Y14.5M AND STD-10811
UNLESS OTHERWISE SPECIFIED
SURFACE ROUGHNESS 125
DIMENSIONS AND TOLERANCES ARE IN INCHES
TOLERANCES: X = ± .1
DECIMALS: .XX = ± .03
.XXX = ± .010
FRACTIONS ± 1/8
ANGULAR ± 2°
DO NOT SCALE DRAWING

REQUESTER: M. DAVENPORT
RESP ENGR: J. PALMER
DESIGN: J. PALMER
DRAWN: N. OLDHAM
PROJECT NO.
SPCL CODE AGR5/6/7
FOR REVIEW/APPROVAL SIGNATURES SEE ECR NO.
EFFECTIVE DATE:

INL Idaho National Laboratory

ATR
ADVANCED GAS REACTOR 5/6/7 (AGR-5/6/7)
TEST TRAIN
ASSEMBLY

SIZE	CAGE CODE	AREA	TYPE	CL	ORIG	DWG-	REV
D	01MF3	533	0670	96	081	604652	-

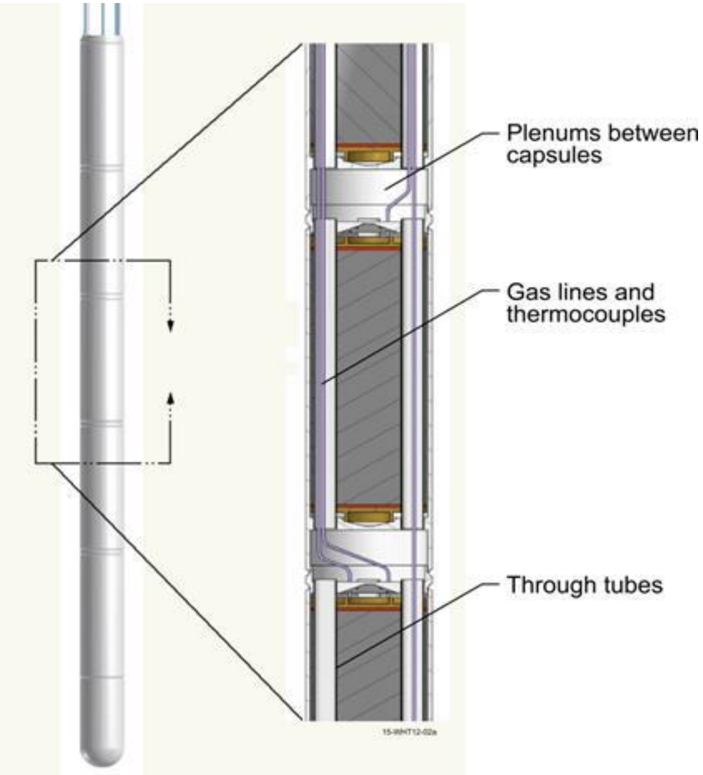
SCALE: NOTED
SHEET 1 OF 5

ATR0812

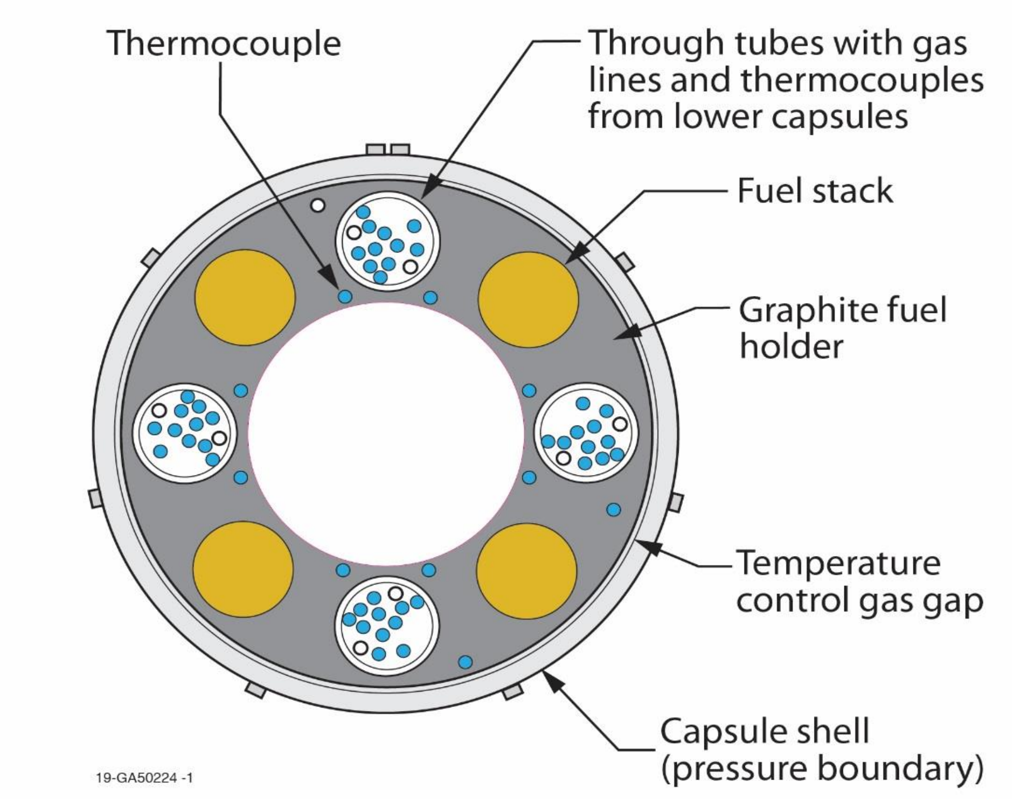
Path: I:\Vaultlocal\projects\ATR\Reactor Experiments\AGR 5-6-7\604652.idw
File:604652R-
Date:7/29/2015

AGR-5/6/7 complete test train assembly

AGR-5/6/7 Test Train Design



Elevation view of AGR-5/6/7 experiment



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

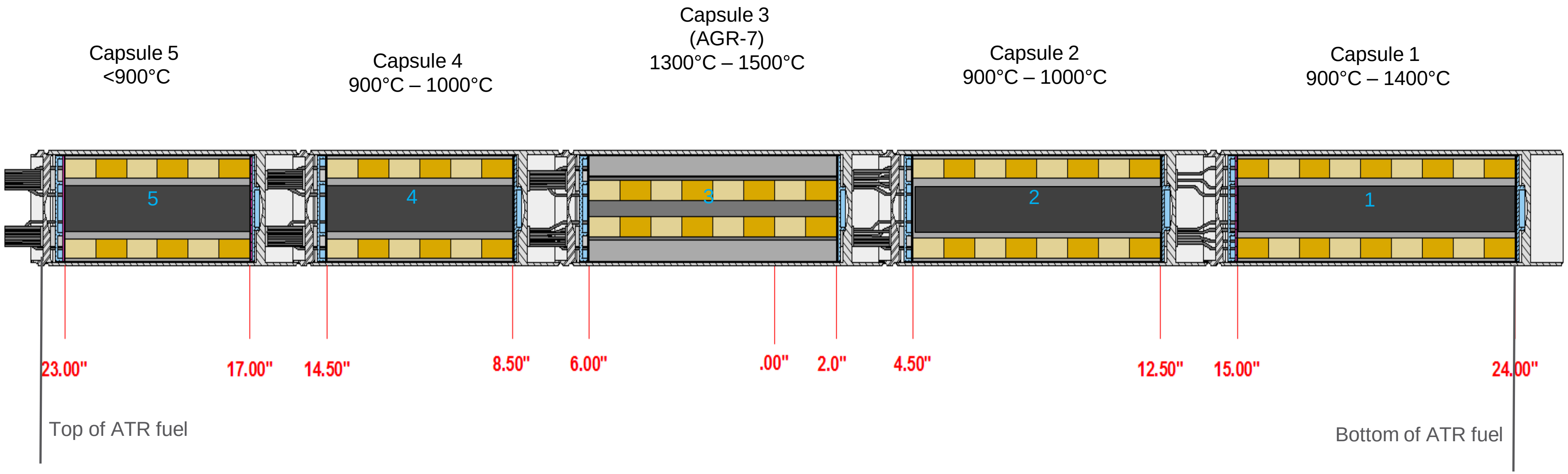
Temperature Distribution (cont)

- To achieve the desired statistical relevance, the program determined that AGR-5/6 should have >500,000 particles and AGR-7 should have >50,000 particles

AGR-5/6	
Desired fraction of particles per temperature range	Number of Particles Based on 500,000 total
30% <900^{o}C	150,000
30% 900^{o}C - 1050^{o}C	150,000
30% 1050^{o}C - 1250^{o}C	150,000
10% 1250^{o}C - 1350^{o}C	50,000
Total	500,000

AGR-7	
Temperature Range	Minimum Number of Particles
1350^{o}C - 1500^{o}C	50,000

Test Train Design



- The test train covers the center 47 inches of the core.
- The design provides for 170 compacts (520,000 particles) in AGR-5/6 and 24 compacts (54,600 particles) in AGR-7. (There are about 3440 particles per compact in capsules 1 and 5, and 2270 particles per compact in the other capsules.)

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 encompassed 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.

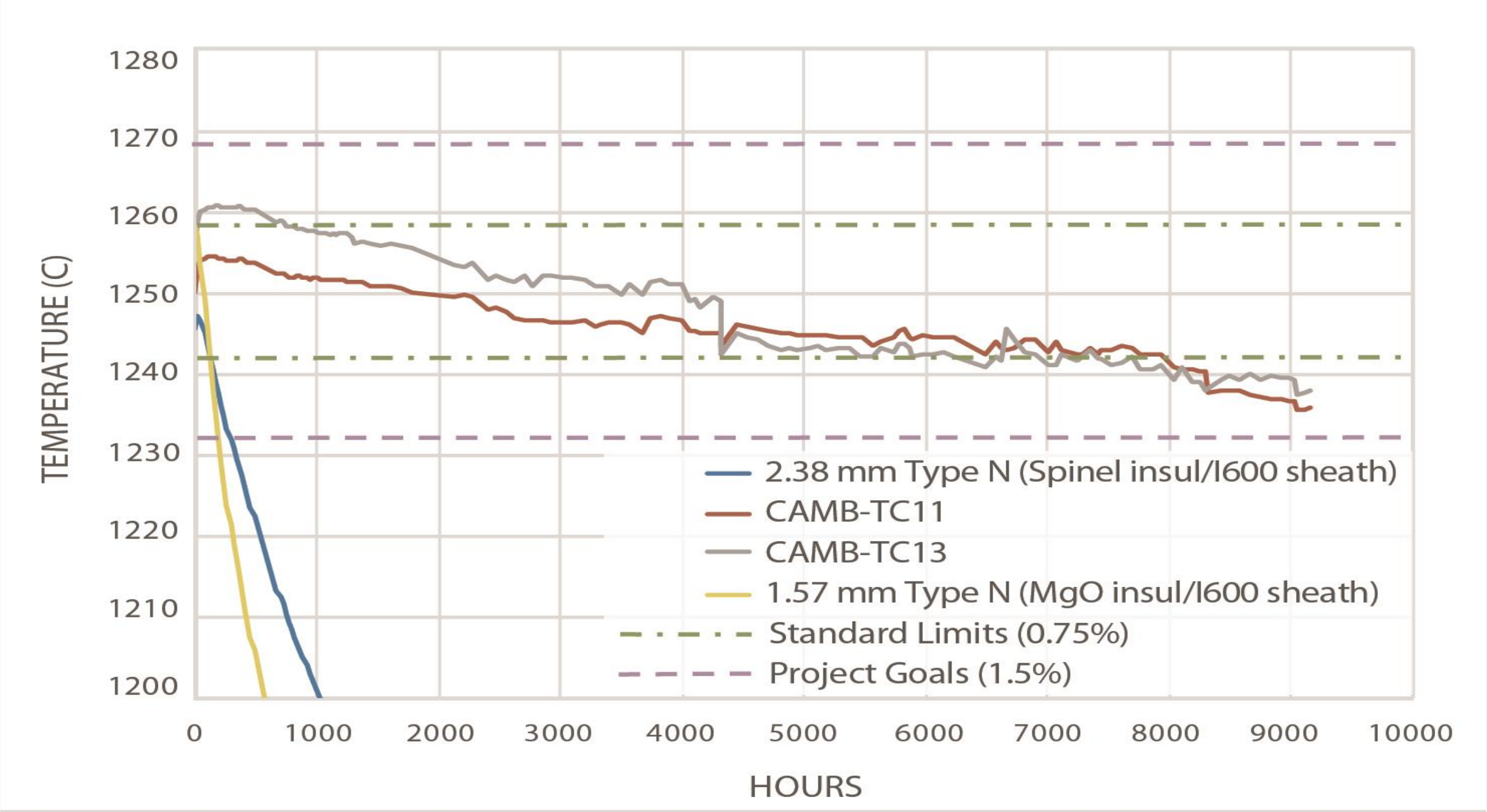
HTIR-TC Long Term Drift Test (furnace at 1250°C)

Cambridge Type N Thermocouples

- This thermocouple type incorporates a special proprietary sheath that limits migration of elements from the sheath to the thermoelements 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)



AGR-5/6/7 supplementary instrumentation

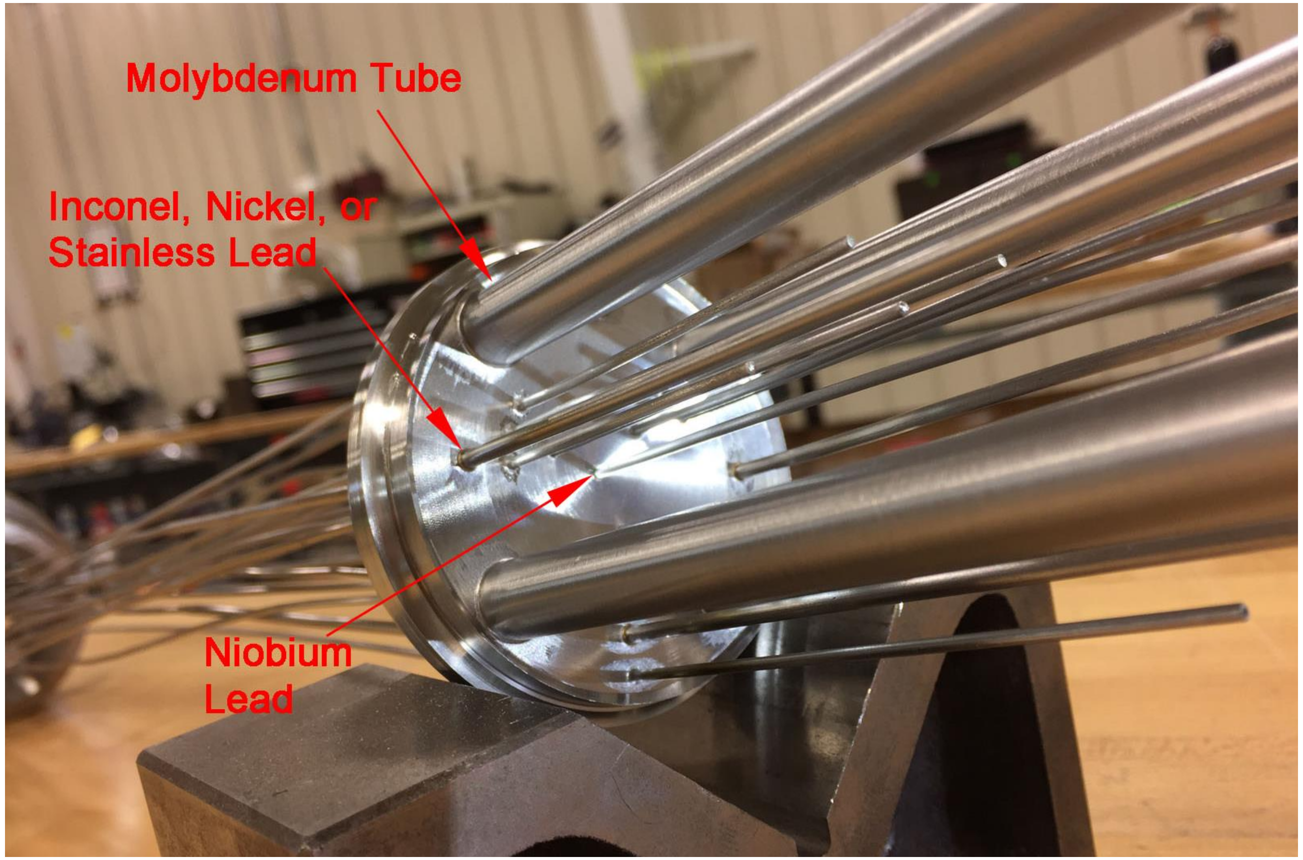
- The design of the AGR-5/6/7 experiment was such that there was some free space in the instrumentation conduits (called “thru-tubes”) which passed through each capsule.
- It was a fairly simple matter to slide “supplementary” instrumentation into these thru-tubes (particularly the thru-tubes of the top capsule).
- This enabled the INL measurement sciences group to obtain valuable irradiation data on three experimental sensor types.

By incorporating supplemental instrumentation, AGR-5/6/7 was used as a cost-effective vehicle to help address in-pile instrumentation gaps

- Real time neutron flux detection
- Performance of optical fibers in high-radiation fields
- Performance of ultrasonic based detectors in high-radiation fields
- Results from these supplementary instruments were mixed (and are beyond the scope of this presentation), but each instrument type functioned for a least a short period, and provided a useable data set for further developmental efforts

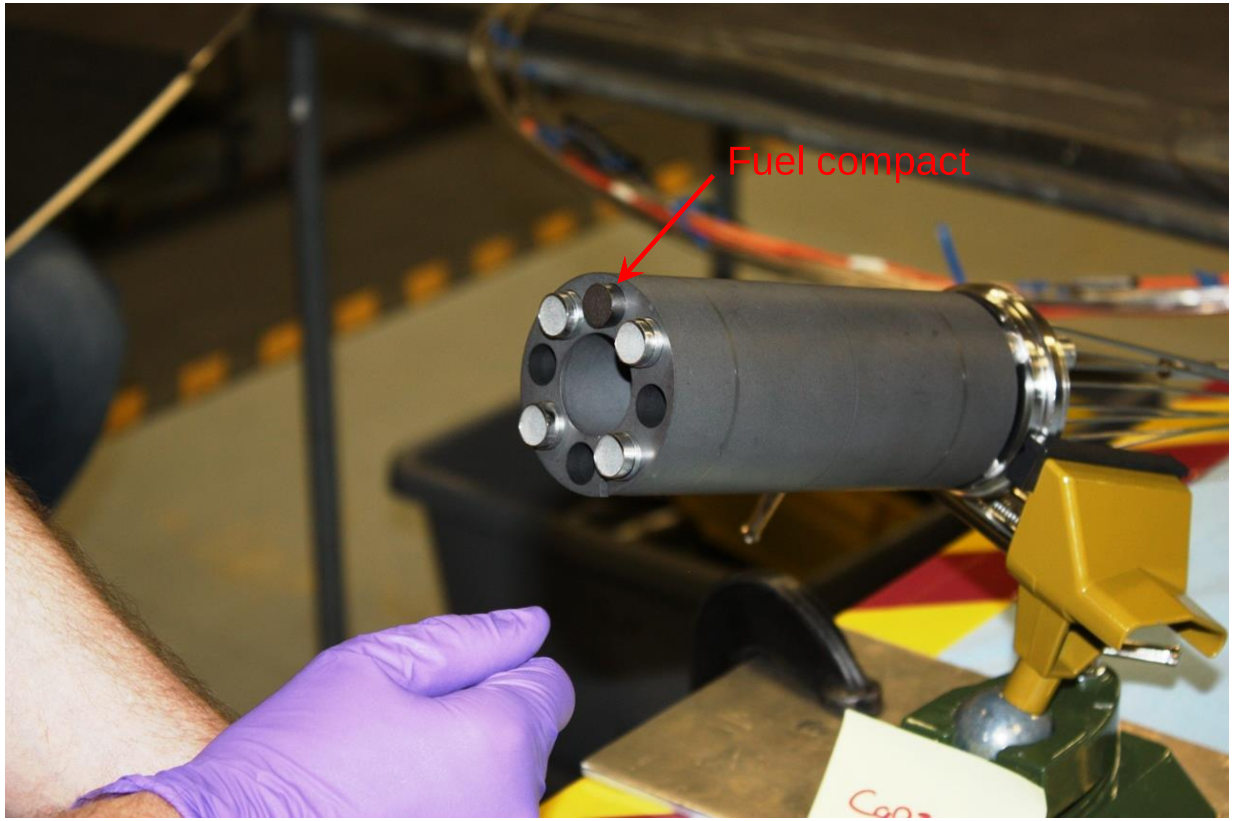
AGR-5/6/7
Assembly highlights

Brazing was done prior to starting assembly

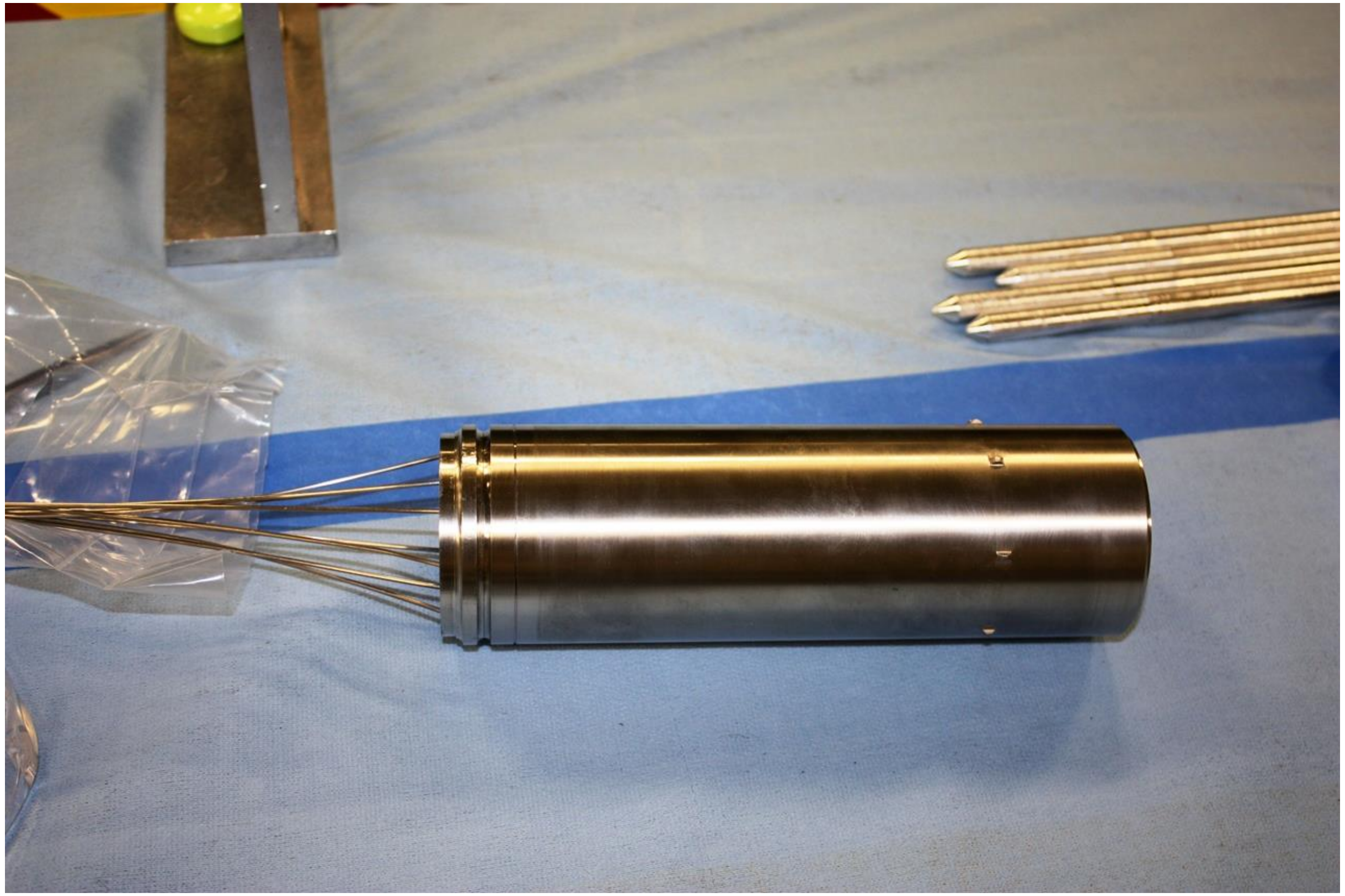


Sliding graphite fuel holders on to brazed heads

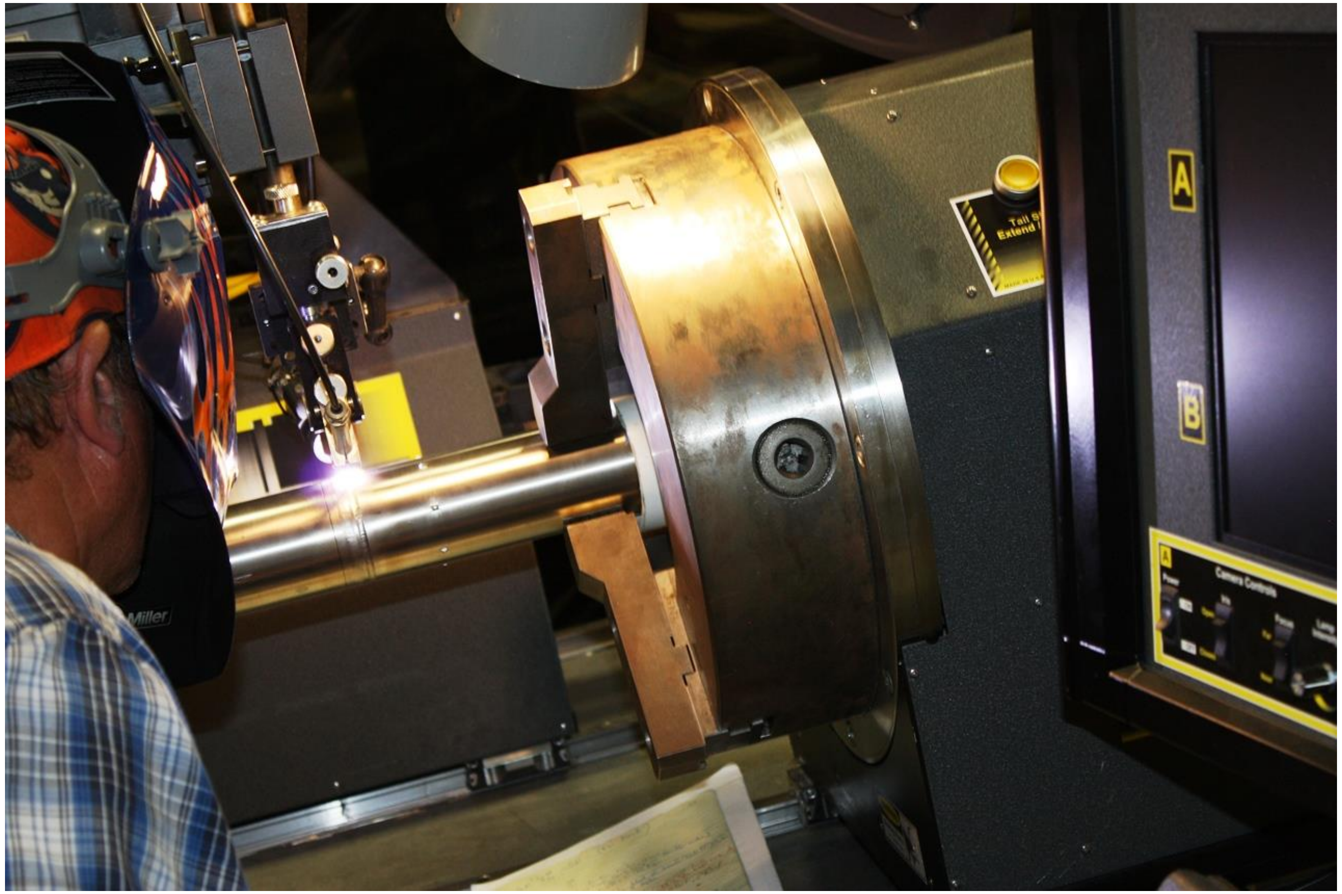
After the graphite fuel holder was slid onto the thermocouples and thru-tubes, the fuel was loaded into the fuel holes



After the capsule shell is slid over the graphite, the assembly is ready for welding



Welding using the automated lathe

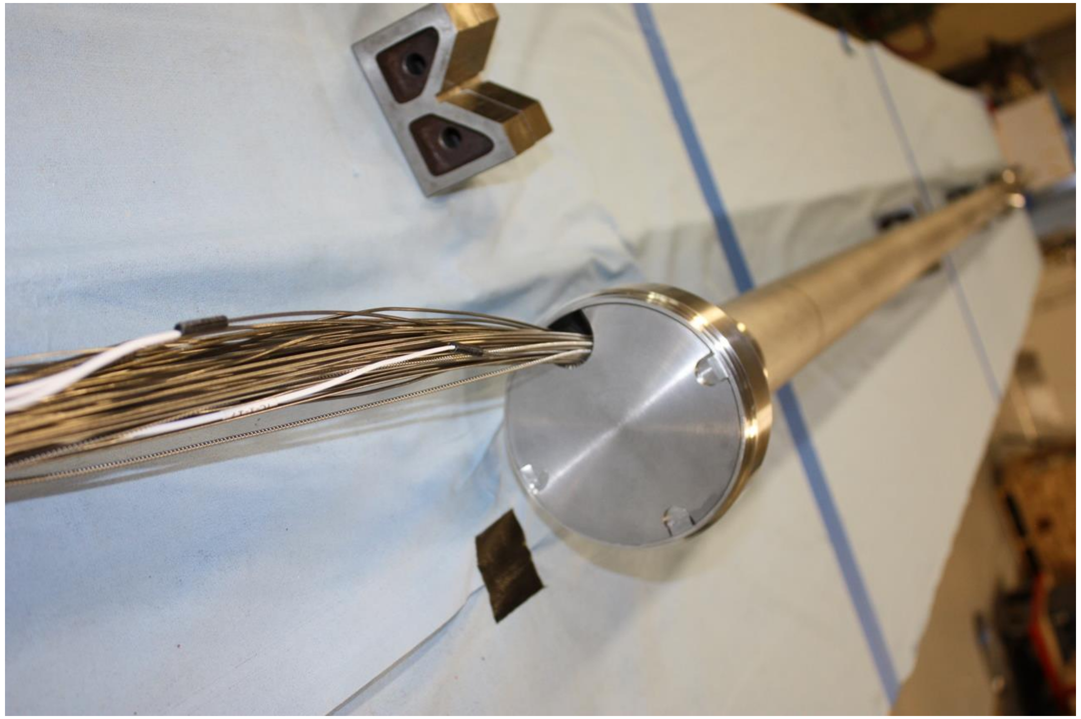


Capsules 1 and 2 welded together

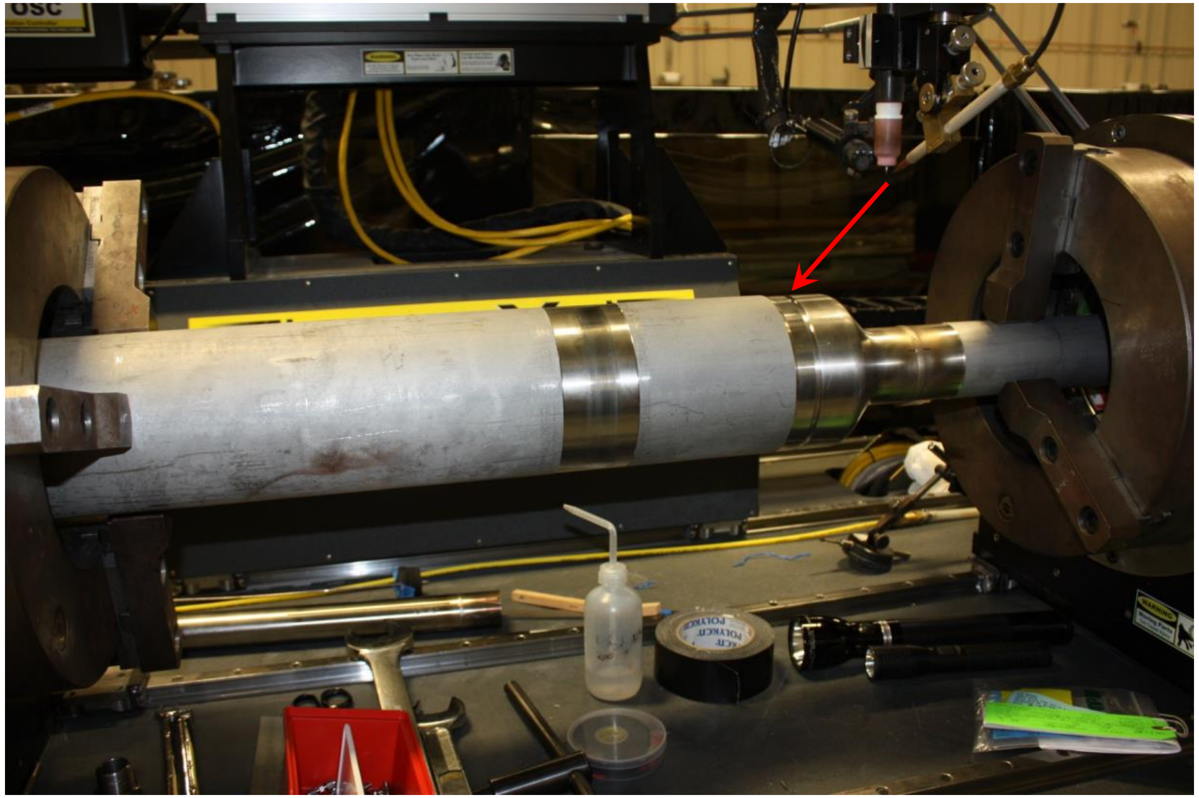
Capsule 5 (top capsule) almost seated

In addition to thermocouples, SPNDs, fiber optic temperature sensors, and ultrasonic temperature sensors were part of these instrumentation bundles

Cabling exiting top tungsten shielding



Last weld setup on welding lathe



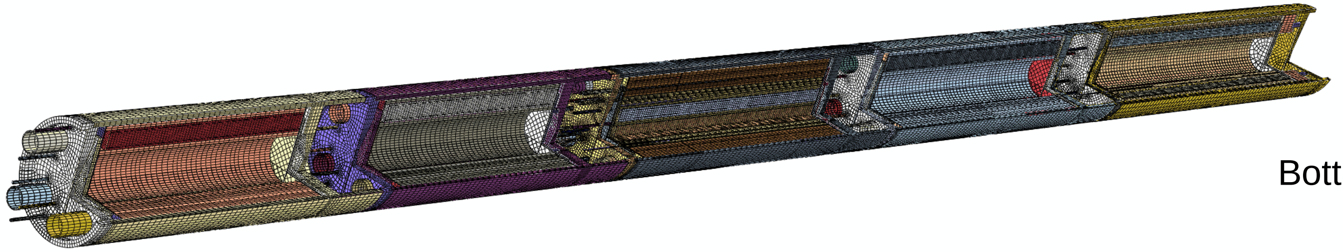
Installing AGR-5/6/7 in ATR

Irradiation Testing Results – First Four Reactor Cycles

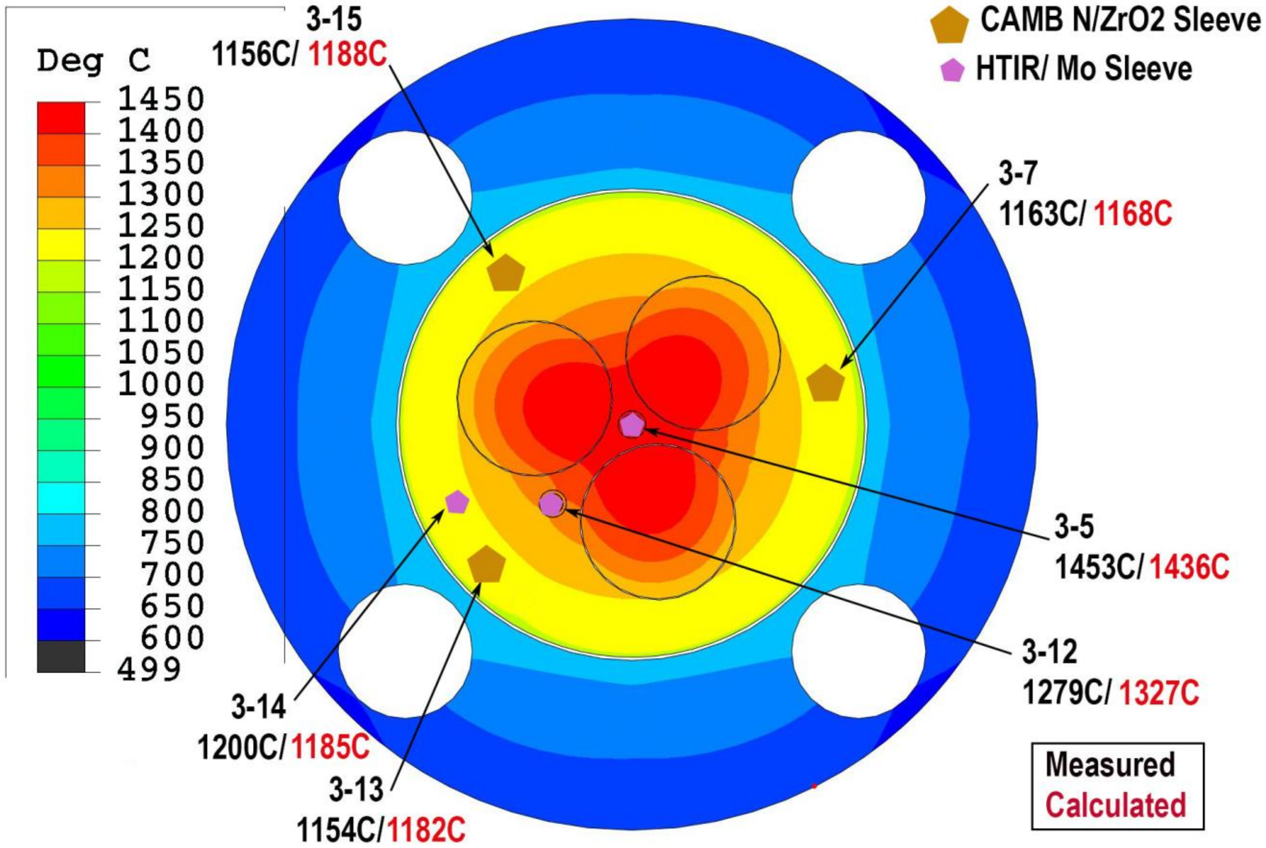
Measured Temperatures Compared to Thermal Model

ABAQUS Finite Element Mesh

- 1,200,000 hexahedral finite element bricks

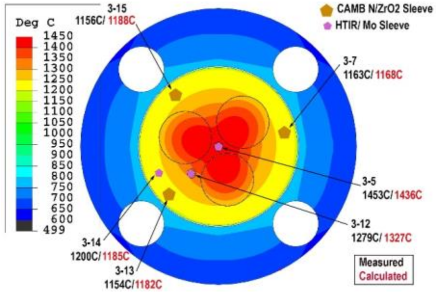


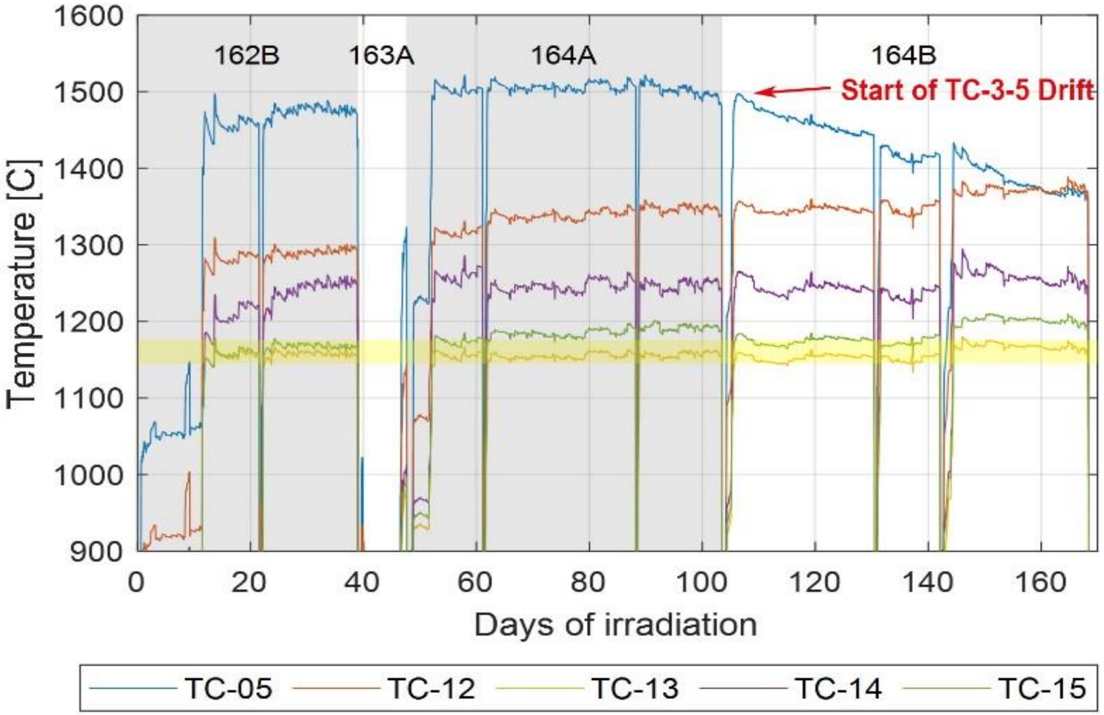
Capsule 3 Thermocouples Measured vs Calculated at Startup



Capsule 3 Selected Thermocouple Trends

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





Take-aways

- The AGR program established temperature requirements early in the design phase.
- A gap in available instrumentation to measure such high temperatures was identified.
- The AGR program funded an extensive developmental and testing program to successfully fill this gap.

Publications summarizing this work:

1. A. J. Palmer, R.S. Skifton, D. C. Haggard, W. D. Swank (INL), M. Scervini (Cambridge University); “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”, International Conference on Advancements in Nuclear Instrumentation, Measurement Methods and their Applications (ANIMMA), Portoroz, Slovenia, June 17-21, 2019, Paper 357654.
2. G. L. Hawkes, J. W. Sterbentz, M. A. Plummer; “Thermal Model Details and Description of the AGR-5/6/7 Experiment”, International Congress on Advances in Nuclear Power Plants (ICAPP-2019), Juan-les-ins, France, May 12-15, 2019.


INL
Idaho National Laboratory