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As-run thermal hydraulics analysis of the EPRI-1 Experiment

Paul Murray, John Howard Jackson

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Idaho National Laboratory

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7. Objective/Purpose:

The EPRI-1 experiment was designed to irradiate various types of reactor pressure vessel steels at a temperature of 288°C (PLN-3934). The specimens were irradiated in an instrumented test train inside a pressurized water loop in the center lobe of the ATR during cycle 157C. Temperature was monitored using thermocouples placed at the top of the test train. Additional temperature indications were obtained by post-irradiation examination of melt wires placed within the test train and spanning the temperature range 239°C to 327°C.

The purpose of this analysis is to calculate specimen temperature using measured data on reactor power and as-run calculations of heating rates of the test train. The accuracy of the model is assessed by comparing the measured and calculated in-pile tube inlet to outlet temperature difference, comparing the measured and calculated thermocouple temperatures, and comparing the calculated specimen temperature to the temperature range indicated by the melt wires.

8. If revision, please state the reason and list sections and/or pages being affected:

9. Conclusions/Recommendations:

A finite element, steady-state heat transfer analysis of the EPRI-1 experiment was performed using ABAQUS. The analysis was performed at four selected days during cycle 157C, using the measured center lobe power, measured coolant flow, measured inlet temperature and pressure, and as-run heating rates, to obtain best-estimate temperatures of the specimens. In order to compensate for uncertainty in the gas gap between the pressure tube and envelope tube, the gap conductance was adjusted to bring into agreement the measured and calculated thermocouple temperatures. This ensures that the thermal analysis correctly predicts the increase in coolant temperature from the IPT inlet to the top of the test train. Moreover, the calculated temperature of the specimens is consistent with the temperature range indicated by the melt wires.

The desired value of the nominal irradiation temperature of the specimens is 288°C. The results of this analysis show that in cycle 157C the average temperature of the specimens varied from approximately 260°C to 340°C due to the axial variation in the heating rate. The average and maximum temperature of each specimen in the test train was calculated at the average center lobe power in cycle 157C and reported in Table 2 of this ECAR. The variation in center lobe power during the cycle was small and therefore had a negligible effect on the specimen temperature. The results may be used in evaluating the temperature-dependence of the crack-growth and tensile test data acquired after irradiation of the specimens.

CONTENTS

APPENDICES

Title: As-Run Thermal-Hydraulic Analysis of the EPRI-1 Experiment

ECAR No.: 3847 Rev. No.: 0 Project No.: 31295 Date: 09/30/2017

PROJECT ROLES AND RESPONSIBILITIES

Project Role	Name (Typed)	Organization	Pages covered (if applicable)
Performer	P. E. Murray	C130	
Checker[a]	C. Hale	C130	All
Independent Reviewer[b]	Not Required		
CUI Reviewer[c]	C. Hale	C130	
Manager[d]	M. A. Lillo	C130	
ATR Experiments[e]	Not Required		
Nuclear Safety[e]	Not Required		
Document Owner[e]	J. H. Jackson	C002	

Responsibilities:

a. Confirmation of completeness, mathematical accuracy, and correctness of data and appropriateness of assumptions.

b. Concurrence of method or approach. See definition, LWP-10106.

c. Concurrence with the document's markings in accordance with LWP-11202.

d. Concurrence of procedure compliance. Concurrence with method/approach and conclusion.

e. Concurrence with the document's assumptions and input information. See definition of Acceptance, LWP-10200.

NOTE: *Delete or mark "N/A" for project roles not engaged. Include ALL personnel and their roles listed above in the eCR system. The list of the roles above is not all inclusive. If needed, the list can be extended or reduced.*

SCOPE OF ANALYSIS AND BRIEF DESCRIPTION

The EPRI-1 experiment was designed to irradiate various types of reactor pressure vessel steels at a temperature of 288°C (PLN-3934). The specimens were irradiated in a non-instrumented test train inside a pressurized water loop in the center lobe of the ATR during cycle 157C. Temperature was monitored using thermocouples placed at the top of the test train. Additional temperature indications were obtained by post-irradiation examination of melt wires placed within the test train and spanning the temperature range 239°C to 327°C.

The purpose of this analysis is to calculate specimen temperature using measured data on reactor power and as-run calculations of heating rates of the test train. The accuracy of the model is assessed by comparing the measured and calculated in-pile tube inlet to outlet temperature difference, comparing the measured and calculated thermocouple temperatures, and comparing the calculated specimen temperature to the temperature range indicated by the melt wires.

DESIGN OR TECHNICAL PARAMETER INPUT AND SOURCES

The technical requirements of the EPRI-1 experiment were initially specified in the project execution plan (PLN-3934). Since the development of the initial project plan, the design and experiment loading had changed significantly. A detailed description of the final design and experiment loading is given in the updated experiment loading plan (PLN-3990). The quality level of the analysis of the test train (non-pressure boundary) components is QL-2 as documented in RTC-000690. Appendix F documents the as-run analysis requirements and will serve as the analysis plan for this ECAR.

EXPERIMENT DESCRIPTION AND OTHER BACKGROUND DATA

A pressurized water loop (PWL) is a closed-loop piping system that penetrates the reactor vessel boundary. The in-pile tube (IPT) portion of the PWL extends from the vessel top head to the vessel bottom head. The standard IPT consists of a double-walled tube (a pressure tube inside an envelope tube) and a flow tube. The pressure and envelope tubes are separated by a helium gas annulus that insulates the pressure tube from the reactor primary coolant. The flow tube is placed inside the pressure tube and contains the in-core test train supported by the hanger rod. The 2A-C loop uses cubicle 2A for the out-of-pile components and the center lobe for the in-pile components of the loop. In this loop, the coolant flows upward in the annulus between the pressure tube and flow tube, changes direction at the flow-reversal above the core, and flows downward through the flow tube and test train.

The first test to be installed in the 2A-C loop is the EPRI-1, EPRI-2, and EPRI-3 experiments that include compact tension (CT), tensile, and Transmission Electron Microscopy (TEM) specimens to be irradiated at 550°F (288°C). Specimen materials include X-750 (inconel), XM-19 (nitronic-50), and stainless steel type 304L. The specimen holder is designed to contain 0.4 inch thick CT specimens and 0.25 inch round tensile specimens, and is a modification of the Bettis SIPT test holder. Four zirconium alloy holders are interlocked to form a 64 inch long test train located at an elevation 24 inches below core mid-plane to 40 inches above core mid-plane. A test stop is located 25 inches below core mid-plane to 87 inches below core mid-plane.

The EPRI test train contains CT specimen packages each of which contain two CT specimens, and tensile specimen packages each of which contain four tensile specimens. Sets of CT and tensile specimen packages are contained in four test holders denoted by its position in the test train – bottom, lower center, upper center, and top holders. The specimens are located at an elevation 24 inches below core mid-plane to 25 inches above core mid-plane since the top holder is only partially filled with specimens.

During irradiation of the EPRI-2 experiment in cycle 153B, the pressure drop across the test train steadily increased during the cycle which eventually required startup of a third loop pump to maintain flow. The subsequent EPRI experiments (EPRI-1 and EPRI-3) were redesigned to reduce the flow restriction where the coolant exits the holder and to reduce misalignment of coolant channels which had led to the increased pressure drop observed in the EPRI-2 experiment. These design modifications reduced the test train pressure drop to an acceptable level in the subsequent EPRI experiments. A detailed description of the design modifications is given in PLN-3990.

The bottom holder (EPRI-1A) contains a flow-through spacer rather than specimens. The lower center holder (EPRI-1B) contains 10 pairs of CT specimens and a set of four tensile specimens. The upper center holder (EPRI-1C) contains 9 pairs of CT specimens. The upper holder (EPRI-1D) contains 4 pairs of CT specimens. Four thermocouples are located in specimens EPRI-1D-1. Melt wires are located in specimens EPRI-1B-3, EPRI-1B-12 and EPRI-1C-10. A detailed description of the experiment loading is given in PLN-3990.

ASSUMPTIONS

Heat loss from the IPT to the reactor primary coolant is larger than predicted using the gap conductance based on nominal dimensions of the gap between the pressure tube and envelope tube. The actual gap conductance is larger than the nominal gap conductance due to the presence of centering nubs on the pressure tube. The gap conductance is also affected by uncertainty in the gas gap due to fabrication tolerances. Moreover, deformation of the pressure tube due to thermal expansion and irradiation swelling will lead to a reduction in the gas gap. Therefore, the conductance is adjusted in order to bring into agreement the measured and calculated values of the temperature of the thermocouples.

The CT specimen assembly consists of two specimens, two side plates, and two screws that fasten the specimens and plates. The assembly is loose-fitting since the screws do not keep the parts in a fixed position. This leads to misalignment of coolant channels between adjacent CT specimens and between the specimens and side plates. The EPRI-1 experiment was reconfigured to reduce misalignment of the CT specimen stacks which reduced the IPT pressure drop. Nonetheless, the melt wires indicated temperatures that are higher than expected which suggests a flow blockage in the narrow channels surrounding the CT specimens. Therefore, the flow rate in these channels is set to zero in order to simulate a flow blockage and to bring into agreement the calculated temperature of the specimens and the temperature range indicated by examination of the melt wires.

SOFTWARE VALIDATION

A finite element heat transfer analysis of the EPRI-1 experiment was performed using ABAQUS version 6.14-2 on a DELL Workstation (“605566” on the INL network). The operating system is Windows 7 Enterprise, and each processor is a quad-core 2.2 GHz Intel Xenon processor. ABAQUS is listed in the INL Enterprise Architecture (EA) repository of qualified scientific and engineering analysis software (EA Identifier 238858). ABAQUS has been validated for thermal analysis of ATR experiments by solving several test problems and verifying the results against analytical solutions provided in heat transfer textbooks. A complete description of the validation test problems is given in ECAR-131. Scripts were developed to automate the execution, data collection, and relative error calculation for each test problem. The scripts were run on computer “605566” and a report file containing the results of validation testing was automatically generated (Appendix E). The test results meet the acceptance criterion that the relative error is less than 3%.

Calculations given in the appendices were performed using Mathcad version 15. This software is used to document engineering calculations on a computer-generated worksheet that automatically performs calculations given user input, provides automatic units checking and conversion, and includes a large library of built-in functions. Formal validation of Mathcad and spreadsheet applications is not required, instead random hand calculations are performed during checking to verify that the computer-generated output is correct (Appendix E in LWP-10200).

ANALYSIS RESULTS

The heating rates of the IPT components and loop coolant outside the holders at 23 MW center lobe power were obtained from the reactor physics analysis developed during the design phase of the EPRI experiment (ECAR-1844). The heating rates of the test train components and loop coolant inside the holders at 21.1 MW center lobe power were obtained from the as-run reactor physics analysis developed after irradiation of the EPRI-1 experiment (ECAR-3326). Heating rates for each component were obtained as a function of position with respect to core mid-plane, and a cosine-shaped profile was used to represent the axial variation in heating. Heating rates at a different power are obtained by linear scaling using the nominal operating heating rates provided in ECAR-1844 and ECAR-3326 as a baseline. Details are given in Appendix A (IPT heating) and Appendix B (test train heating).

Data on material properties are obtained from the handbooks and databases listed in the references and are given in Appendices C.1 and C.2. The heat transfer coefficients for turbulent forced convection in the IPT are calculated in Appendices C.3, C.4 and C.5. The mass flow rates in the IPT coolant channels are calculated in Appendices C.6 and C.7. The conductance of the insulating helium gap between the pressure and envelope tubes is calculated in Appendix C.8. The heat transfer coefficients between the IPT and the reactor primary are calculated in Appendices C.9 and C.10. The heating profiles developed in Appendices A and B are used in Appendices C.11 and C.12 to determine the heating rates at core mid-plane.

Reactor power, coolant flow, pressure drop, and coolant temperature were obtained from the Loop Data Acquisition System (LDAS). The data at 12 hour intervals was computed by averaging the data at 5 minute intervals over each 12 hour period and is shown in Appendix D. Coolant flow was maintained at 30 gpm during the cycle with an IPT pressure drop that varied from approximately 140 psi to 170 psi. The center lobe power at four selected days in the cycle, along with the average power and the maximum power during the cycle, are reported in Appendices C.13. The analysis consists of six steps: steps 1 through 4 represent the temperature distribution at four selected days during the cycle, step 5 represents the temperature distribution at the cycle-average center lobe power (21.1 MW), and step 6 represents the temperature distribution at the cycle-maximum center lobe power (21.58 MW).

A finite element, steady-state heat transfer analysis of the IPT and EPRI-1 test train was performed using ABAQUS. The 8-node linear brick element was used to model the test train components and the 4-node linear shell element was used to model the IPT components. The 8-node forced convection brick element was used to model the loop coolant and reactor primary coolant with a prescribed mass flow rate. The model geometry and finite element mesh of the EPRI-1 test train in cycle 157C is shown in

Fig. 1. In this figure, the holders are blue, the CT specimens are green, the tensile specimens are red, the cruciform spacers are orange, and the flow-through spacer is yellow.

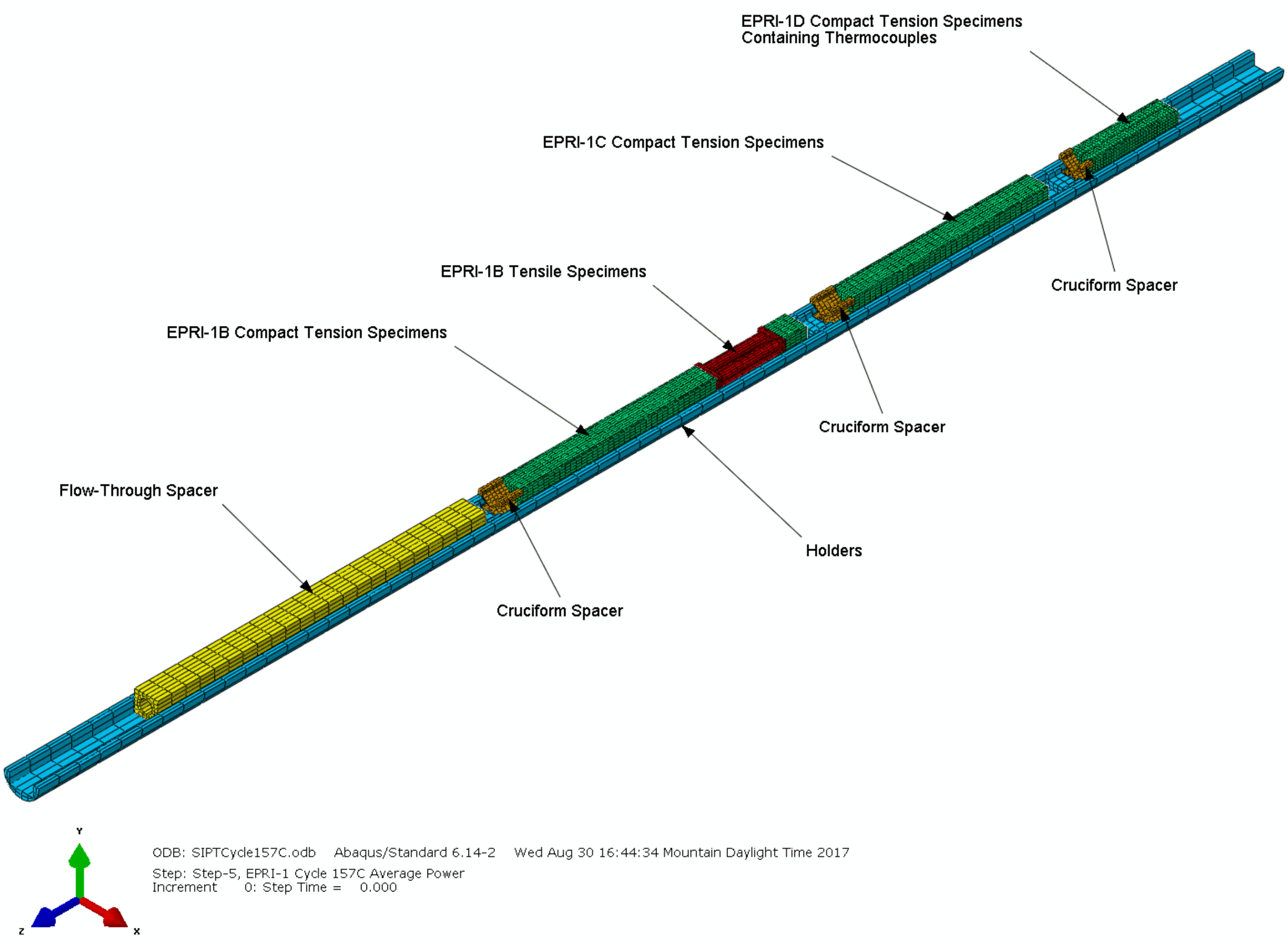

Figure 1. Finite element mesh of the EPRI-1 test train in cycle 157C.

A thermal analysis was performed at four selected days during each cycle, using the measured center lobe power, measured coolant flow, measured inlet temperature and pressure, and as-run heating rates, to obtain best-estimate temperatures of the specimens. A comparison of the measured and calculated temperature increase from the IPT inlet to outlet is shown in Fig. 2, and a comparison of the measured and calculated thermocouples temperatures is shown in Fig. 3. Since the thermocouples are embedded in a CT specimen and are located close to the surface of the specimen, the thermocouples essentially indicate the temperature of coolant surrounding the specimen. These results confirm that the thermal analysis correctly predicts the increase in coolant temperature from the IPT inlet to the top of the test train where the thermocouples are located.

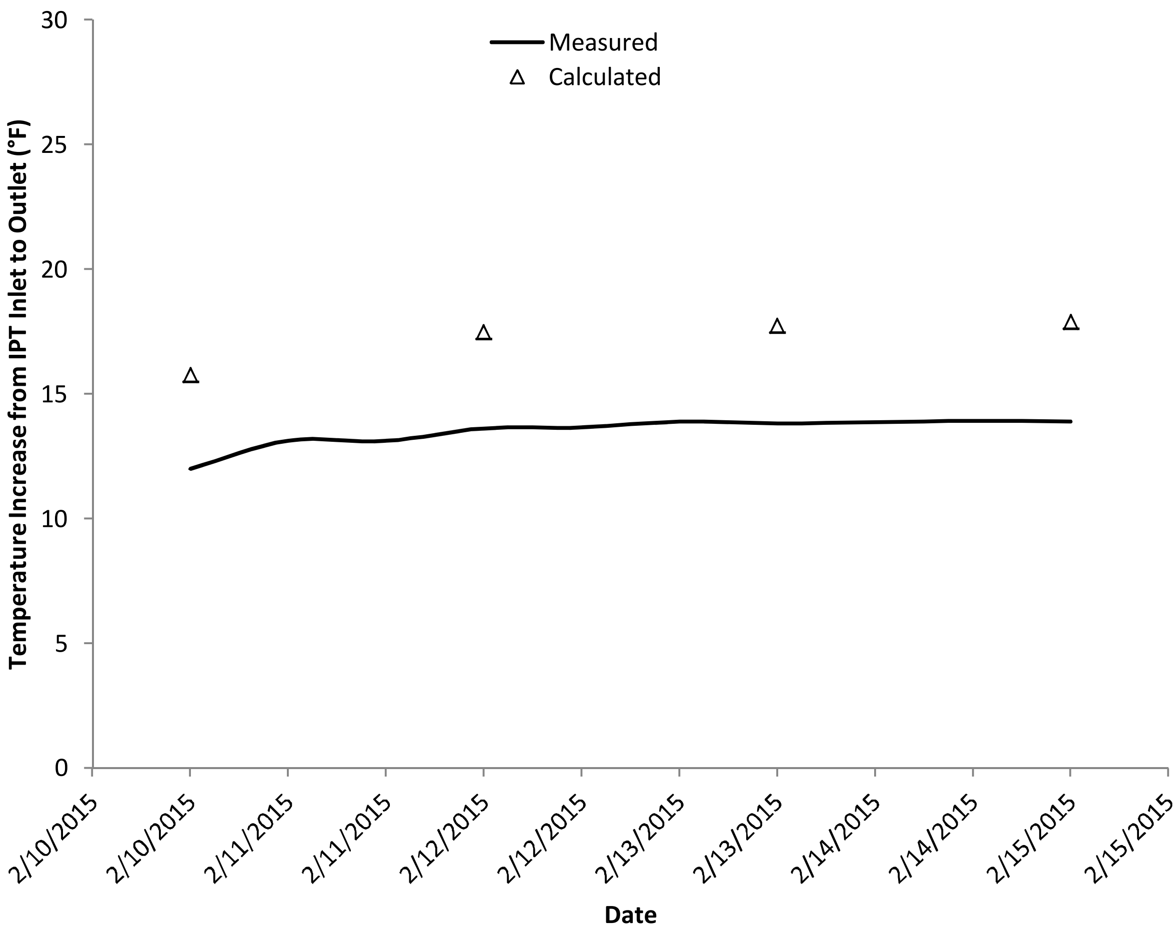

Figure 2. Measured and calculated increase in coolant temperature (°F) in cycle 157C.

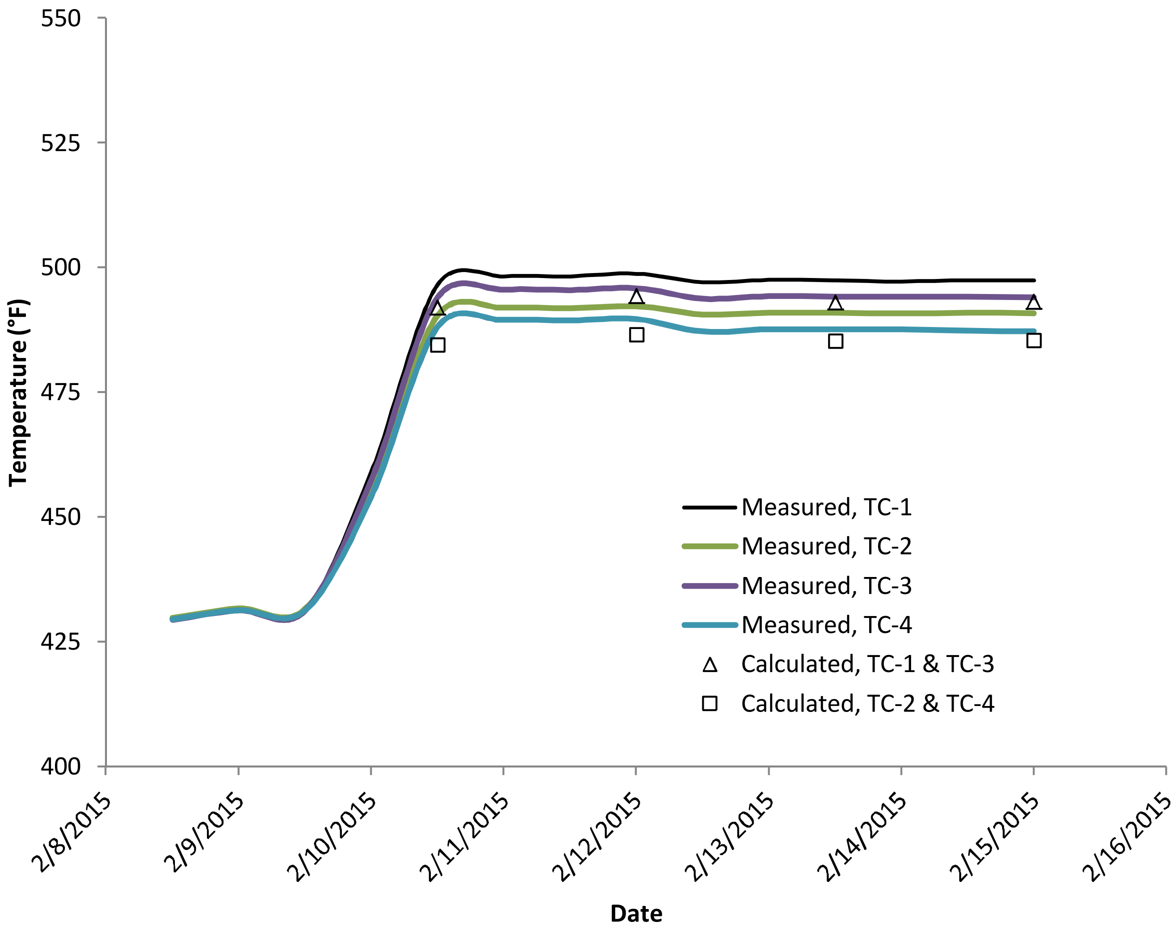

Figure 3. Measured and calculated temperature (°F) of thermocouples in cycle 157C.

The calculated average temperature and maximum temperature of the specimens, at the average center lobe power during cycle 157C, are shown in Fig. 4. The results indicate that the temperature of most of the specimens in the test train exceeded the desired temperature of 288°C due to the flow blockage caused by misalignment of the coolant channels. The significant variation in specimen temperature is due to the axial heating profile and the increase in coolant temperature as it flows through the test train. Moreover, the temperature of the tensile specimens at 4 inches above core mid-plane is significantly less than the temperature of the adjacent CT specimens.

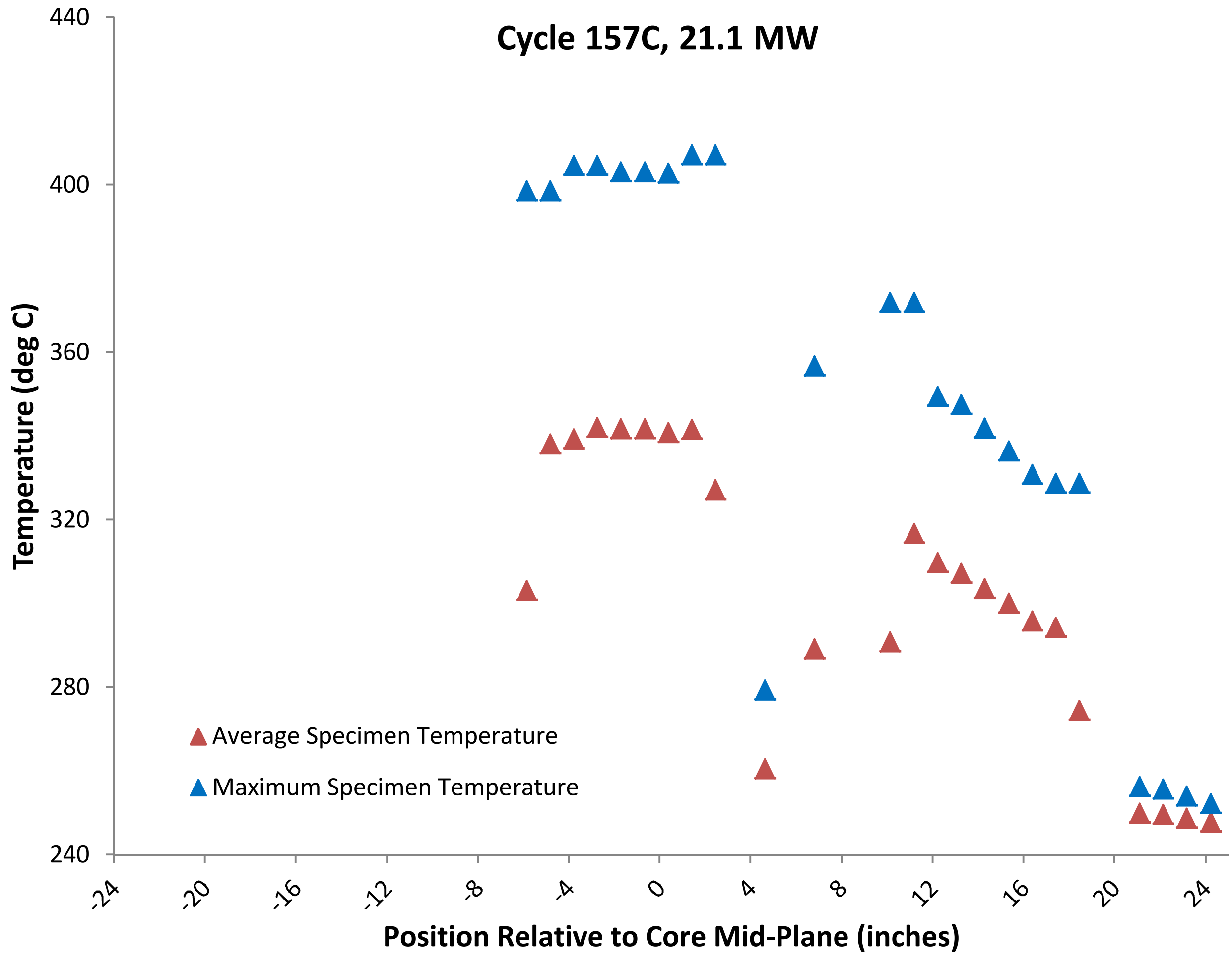

Figure 4. Calculated average temperature (°C) of specimens in cycle 157C.

A contour plot of the temperature of the specimens at the average center lobe power during cycle 157C (21.1 MW) is shown in Fig. 5. In this figure, the geometry was cut to reveal one-half of the CT specimens in order to show their internal temperature. These results indicate that the temperature of the EPRI-1B CT specimens are significantly higher than the EPRI-1C specimens.

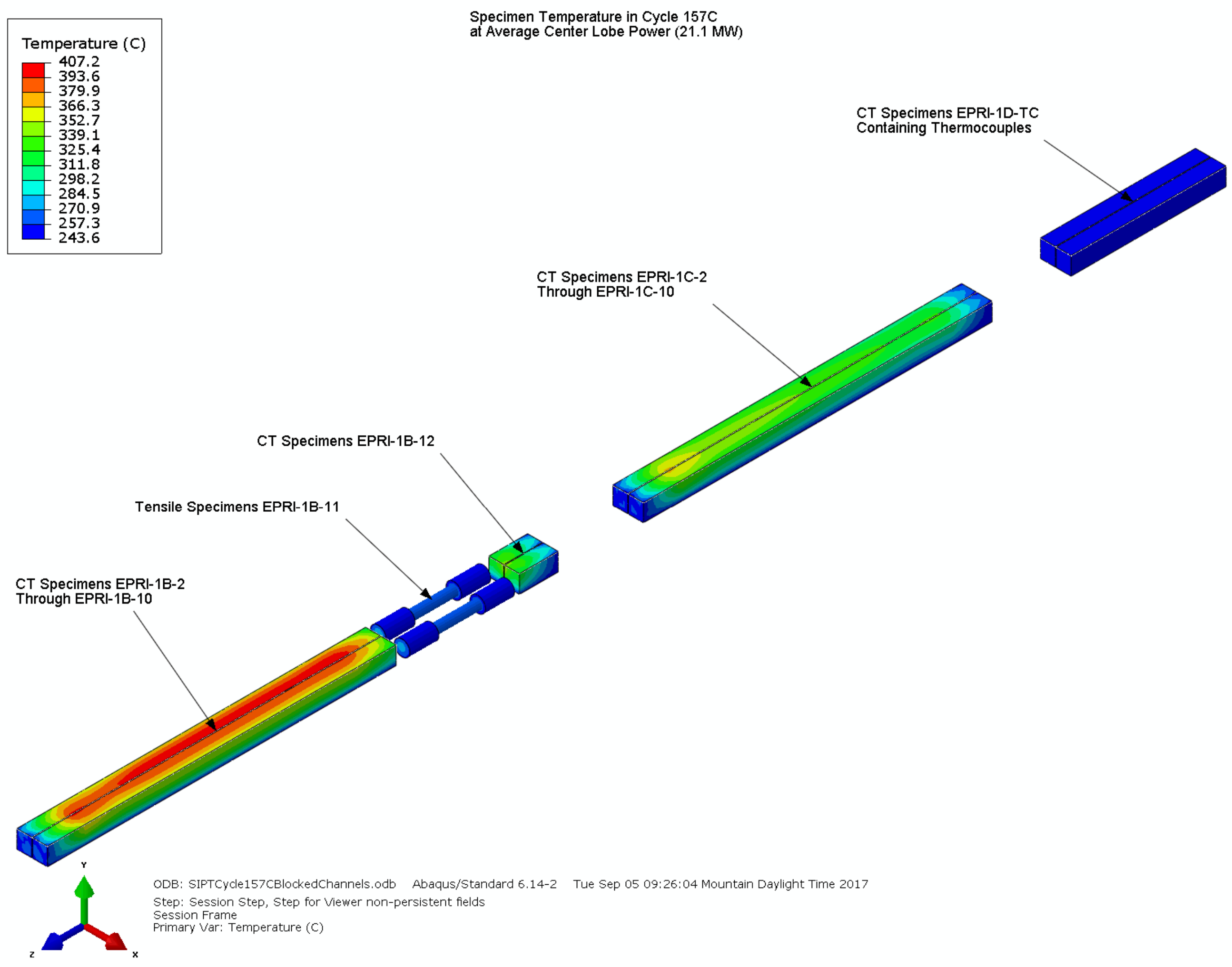

Figure 5. Calculated temperature (°C) of specimens in cycle 157C at average cycle power.

The temperature of the specimens is indicated by melt wires placed at various locations in the test train. Data obtained from the Loop Data Acquisition System at 5 minute intervals shows that the maximum center lobe power was 21.58 MW and occurred at 09:00 hours on 02/13/2015. Since the highest temperature in the test train occurred at the time of maximum power, the melt wires indicate temperature at the time of maximum power. The test train contains twelve melt wires – four melt wires in specimen EPRI-1B-3, four melt wires in specimen EPRI-1B-12, and four melt wires in specimen EPRI-1C-10. The author visually examined the melt wires at the HFEF on February 13, 2017. Table 1 shows the results of the melt wire examinations. All wires showed indications of melting. Therefore, the melt wires indicate that the maximum temperature in specimen EPRI-1B-3 and specimen EPRI-1B-12 is greater than 327°C and the maximum temperature in specimen EPRI-1C-10 is greater than 303°C.

Table 1. Results of melt wire examinations.

Location of melt wire in test train	Melt Wire (elemental composition in weight %)	Melting Temperature (°C)	Calculated Average Specimen Temperature (°C)	Calculated Maximum Specimen Temperature (°C)	Melted during irradiation
EPRI-1B-3 north 2	90 Pb 10 Sb	252.4°C			yes
EPRI-1B-3 north 3	100 Pb	327.5°C			yes
EPRI-1B-3 south 2	100 Bi	271°C			yes
EPRI-1B-3 south 3	90 Pb 5 Ag 5 Sn	302.9°C	340.1	402.0	yes
EPRI-1B-12 north 2	90 Pb 10 Sb	252.4°C			yes
EPRI-1B-12 north 3	100 Pb	327.5°C			yes
EPRI-1B-12 south 2	100 Bi	271°C			yes
EPRI-1B-12 south 3	90 Pb 5 Ag 5 Sn	302.9°C	290.2	359.2	yes
EPRI-1C-10 north 2	90 Pb 10 Sb	252.4°C			yes
EPRI-1C-10 north 3	90 Pb 5 Ag 5 Sn	302.9°C			yes
EPRI-1C-10 south 2	95 Sn 5 Sb	238.6°C			yes
EPRI-1C-10 south 3	100 Bi	271°C	275.1	330.5	*

* Quartz capsule damaged; unable to see melt wire.

A contour plot of the temperature of the melt wire specimens at the maximum center lobe power in cycle 157C is shown in Fig. 6. The calculated maximum temperature of the specimens containing melt wires exceeds the melting temperature of the melt wires. This result gives credibility to the assumption of a flow blockage in the narrow channels surrounding the CT specimens. If those channels were not assumed to be blocked, the thermal analysis would predict temperatures much less than those indicated by the melt wires.

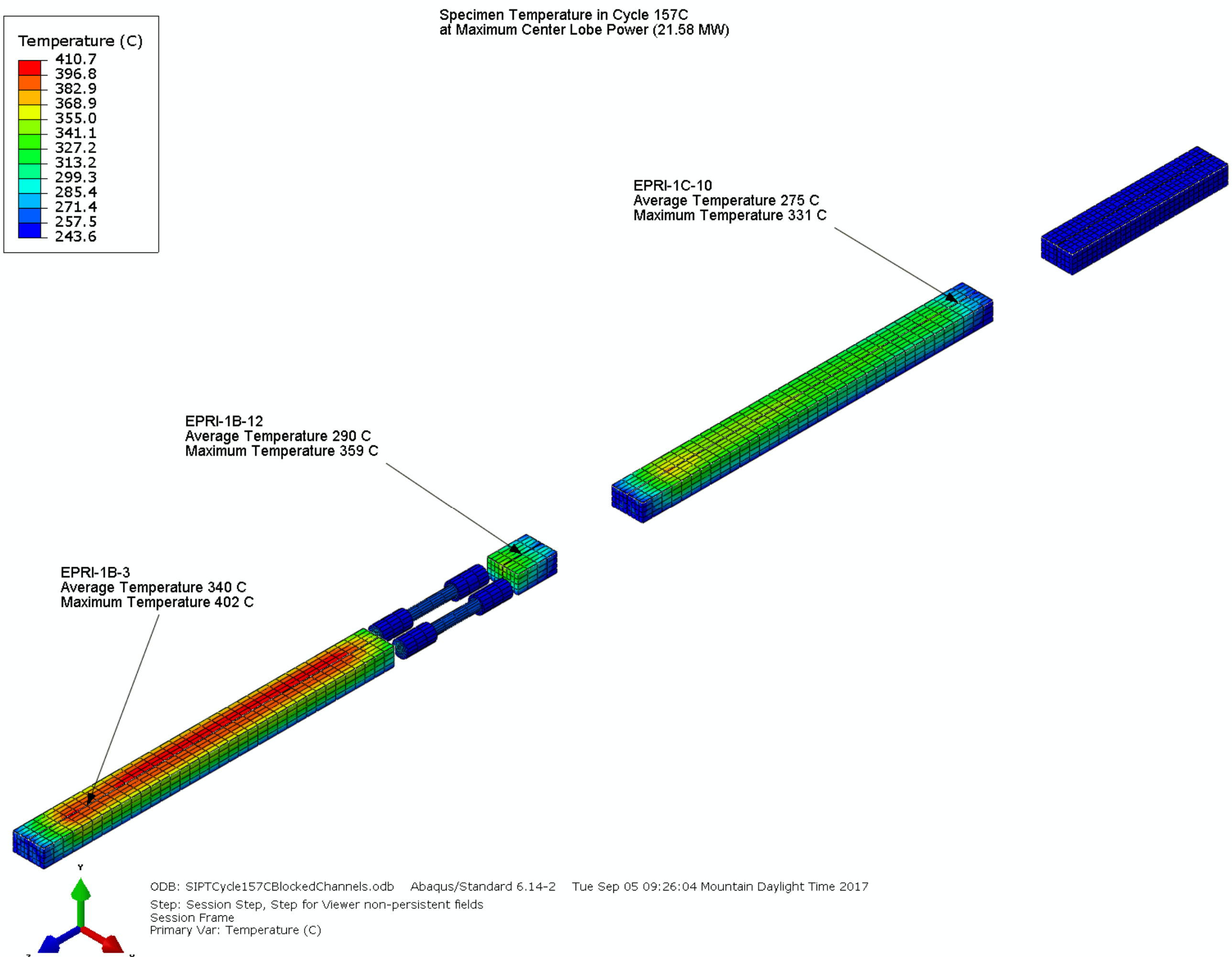

Figure 6. Calculated temperature (°C) of specimens containing melt wires at maximum cycle power.

The average and maximum temperature of each specimen in the test train at the average center lobe power in cycle 157C is reported in Table 2. The variation in center lobe power during the cycle was small and therefore had a negligible effect on the specimen temperature. These results may be used in evaluating the temperature-dependence of the crack-growth and tensile test data acquired after irradiation of the specimens.

Table 2. Calculated temperature (°C) of specimens in cycle 157C.

Specimen Identifier	Average Specimen Temperature at 21.1 MW Center Lobe Power	Maximum Specimen Temperature at 21.1 MW Center Lobe Power
EPRI-1B-2	303	399
EPRI-1B-3	338	399
EPRI-1B-4	339	405
EPRI-1B-5	342	405
EPRI-1B-6	342	403
EPRI-1B-7	342	403
EPRI-1B-8	341	403
EPRI-1B-9	342	407
EPRI-1B-10	327	407
EPRI-1B-11	261	279
EPRI-1B-12	289	357
EPRI-1C-2	291	372
EPRI-1C-3	317	372
EPRI-1C-4	310	350
EPRI-1C-5	307	348
EPRI-1C-6	304	342
EPRI-1C-7	300	336
EPRI-1C-8	296	331
EPRI-1C-9	294	329
EPRI-1C-10	275	329
EPRI-1D-1	250	256
EPRI-1D-2	250	256
EPRI-1D-3	249	254
EPRI-1D-4	248	252

CONCLUSIONS

A finite element, steady-state heat transfer analysis of the EPRI-1 experiment was performed using ABAQUS. The analysis was performed at four selected days during cycle 157C, using the measured center lobe power, measured coolant flow, measured inlet temperature and pressure, and as-run heating rates, to obtain best-estimate temperatures of the specimens. In order to compensate for uncertainty in the gas gap between the pressure tube and envelope tube, the gap conductance was adjusted to bring into agreement the measured and calculated thermocouple temperatures. This ensures that the thermal analysis correctly predicts the increase in coolant temperature from the IPT inlet to the top of the test train. Moreover, the calculated temperature of the specimens is consistent with the temperature range indicated by the melt wires.

The desired value of the nominal irradiation temperature of the specimens is 288°C. The results of this analysis show that in cycle 157C the average temperature of the specimens varied from approximately 260°C to 340°C due to the axial variation in the heating rate. The average and maximum temperature of each specimen in the test train was calculated at the average center lobe power in cycle 157C and reported in Table 2 of this ECAR. The variation in center lobe power during the cycle was small and therefore had a negligible effect on the specimen temperature. The results may be used in evaluating the temperature-dependence of the crack-growth and tensile test data acquired after irradiation of the specimens.

DATA FILES

The ABAQUS files containing the models created for this analysis are stored on the HPC file server in directory "/projects/atr_exp/EPRI-1." The files created for each analysis case are listed in Table 3. ABAQUS Python scripts were created to read an ABAQUS output file and calculate the maximum temperature and volume average temperature of the specimens. The scripts "AbaqusDataAvgTemp.py" and "AbaqusDataMaxTemp.py" calculate the average and maximum specimen temperature and write the results to a file having the same name as the ABAQUS output file but with a ".data" extension. The scripts and data files are stored in the same directory as the ABAQUS files.

Table 3. ABAQUS/CAE model files and ABAQUS input and output analysis files.

File name	Description
SIPT.cae, SIPT.jnl	Model files for cycle 157C
SIPTCycle157C.inp, SIPTCycle157C.odb	Analysis files for cycle 157C

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DRAWINGS

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600552, "ATR Standard In-Pile Tube Closure Housing Detail," Rev. 0.

600553, "ATR Standard In-Pile Tube Insulating Jacket Details and Assembly," Rev. 0.

600554, "ATR Standard In-Pile Tube Pressure Tube Details and Assembly," Rev. 0.

600561, "ATR Standard In-Pile Tube Flow Tube Details and Assembly," Rev. 1.

601025, "ATR Center Flux Trap Baffle and N-16 Tube Housing Assemblies and Details," Rev. 5.

601511, "ATR NSUF In-Pile Tube EPRI Test Train Assemblies," Rev. 6.

601516, "ATR NSUF In-Pile Tube Test Train Holder Bottom Detail," Rev. 1.

601517, "ATR NSUF In-Pile Tube Test Train Nose Piece Detail," Rev. 0.

601525, "ATR NSUF In-Pile Tube Test Train Test Stop Assembly and Details," Rev. 0.

601546, "ATR NSUF In-Pile Tube Test Train EPRI 1, 2, and 3 Project Back-up and Monitor Package Details and Assemblies," Rev. 4.

601547, "ATR NSUF In-Pile Tube Test Train EPRI 1, 2, and 3 Tensile Specimen Package Details and Assemblies," Rev. 4.

601760, "ATR NSUF In-Pile Tube Test Train EPRI-1 In-Core Assembly," Rev. 2.

601755, "ATR NSUF In-Pile Tube Test Train EPRI-2 In-Core Assembly," Rev. 1.

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601756, "ATR NSUF In-Pile Tube Test Train Experiment Holder Assemblies," Rev. 3.

601757, "ATR NSUF In-Pile Tube Test Train Test Holder Body Details," Rev. 0.

601758, "ATR NSUF Project Back-up Compact Tension Specimen Details," Rev. 3.

601750, "ATR NSUF In-Pile Tube Test Train EPRI-1 Stack-up Assemblies," Rev. 3.

601751, "ATR NSUF In-Pile Tube Test Train EPRI-2 Stack-up Assemblies," Rev. 2.

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604232, "ATR NSUF In-Pile Tube Test Train EPRI-1/EPRI-3 Top Specimen Assembly and Details," Rev. 0.

604444, "ATR NSUF In-Pile Tube Test Train EPRI Rounded Tensile Specimen Package Details and Assembly," Rev. 2.

604447, "ATR NSUF EPRI Cruciform Spacer Details," Rev. 2.

604703, "ATR EPRI Reconfiguration Centering Spacer Assembly and Details," Rev. 2.

759261, "ATR NSUF In-Pile Tube Test Train Slotted Standard Hanger Rod Spacer Details," Rev. 1.

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