BLIND PHASE RESULTS FOR TRANSIENT SIMULATIONS OF THE FFTF LOSS OF FLOW WITHOUT SCRAM TEST #13

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Abstract

Twenty-five organizations from thirteen countries participate in the International Atomic Energy Agency coordinated research project for benchmark analysis of the Fast Flux Test Facility Loss of Flow Without Scram Test #13. The blind phase of the benchmark project concluded in October 2020. During the blind phase, each participant was tasked with performing their own independent model development and calculations of LOFWOS Test #13. The blind phase results were evaluated for agreement with the measured test data and amongst collective participant results. For some parameters, many participants achieved relatively good agreement with the measured data while for other parameters, fewer participants successfully predicted the measurements. The initial blind phase results provide confidence that many participants captured the transient progression of LOFWOS Test #13 well and that with further modeling improvement during the open phase, discrepancies with the measured test data can be reduced.

1. INTRODUCTION

In 2018, the International Atomic Energy Agency (IAEA) established a coordinated research project (CRP) for benchmark analysis of the Fast Flux Test Facility (FFTF) Loss of Flow Without Scram (LOFWOS) Test #13 [1,2,3]. Initiated at half power and full flow, LOFWOS Test #13 was an unprotected loss of flow without scram test that began when the three primary sodium pumps were tripped. Although the control rods were prevented from scramming, negative reactivity introduced by the Gas Expansion Modules (GEM), radial core expansion, and other reactivity feedbacks was sufficient to terminate the fission process and reduce power until natural circulation could be established to cool the reactor core.

Argonne National Laboratory and Pacific Northwest National Laboratory are the lead technical coordinators for the CRP. Twenty-five organizations from thirteen countries participate in the CRP, for which the blind phase of the project was recently concluded [4]. During the blind phase, each participant was tasked with performing their own independent model development and calculations of LOFWOS Test #13 using the information provided in the benchmark specification, but without the measured data. Only the information provided in the benchmark specification was to be used during the blind phase. A variety of parameters were selected for participants to calculate and submit during the blind phase. These parameters were compared both against the values other participants calculated, i.e. code-to-code comparisons, as well as against measured or calculated test data when available. The paper presents the blind phase results and comparisons of the participants' transient simulations. Additional blind phase results for the neutronics component of the benchmark are presented in Reference 5.

2. OVERVIEW OF FFTF AND LOFWOS TEST #13

The Fast Flux Test Facility at the Hanford site in Washington was designed by the Westinghouse Electric Corporation for the U.S. Department of Energy (DOE) [6]. FFTF was a 400 MW thermal powered, oxide-fueled, liquid sodium cooled test reactor, built to assist development and testing of advanced fuels and materials for fast reactors. The reactor did not generate electricity, instead discharging heat to the atmosphere via air-cooled dump heat exchangers (DHX). After reaching criticality in 1980, FFTF operated until 1992, providing DOE with the means to test fuels, materials, and other components in a high fast neutron flux environment. FFTF was shut down in 1993 having completed most of its design missions.

In July 1986, a series of unprotected transients were performed in FFTF as part of the Passive Safety Testing (PST) program. Among these were thirteen unprotected loss of flow without scram tests with the plant protection system intentionally disabled. The goals of this program included confirming the safety margins of FFTF as a liquid metal reactor, providing data for computer code validation, and demonstrating the inherent and passive safety benefits of its specific design features.

LOFWOS Test #13 was performed on July 18, 1986. Starting from 50% power and 100% flow, the test officially began when the three primary sodium pumps were simultaneously tripped, causing flow through the core to decrease and the power-to-flow ratio to increase. One minute before the official start of the test, dump heat exchanger blower speeds were reduced and DHX sodium outlet temperatures began to increase. The blower speeds were modified before the primary pumps were tripped in order to maintain a relatively constant core inlet temperature when the pumps did trip.

3. BLIND PHASE RESULTS

During the blind phase, each participant was tasked with performing their own independent model development and calculations of FFTF LOFWOS Test #13. Only the information provided in the benchmark specification was to be used during the blind phase. In addition to the model development and transient simulation activities for the loss of flow test, there was an optional neutronics benchmark component for which participants could submit results. Results from the blind phase of the neutronics component of the benchmark are presented in Reference 5.

Table 1 lists which parts of the benchmark each participant submitted results for. Nearly all participants submitted results for the blind phase of the benchmark. 18 organizations submitted transient test predictions, 11 organizations submitted results for the neutronics component of the benchmark, and 9 organizations submitted results for both.

The blind phase results were evaluated for agreement with the measured test data and amongst collective participant results. The figures below illustrate key blind phase test predictions. Measured test data is represented by a thick yellow line when measurements were available. For some parameters, many participants achieved relatively good agreement with the measured data while for other parameters, fewer participants successfully predicted the measurements. The initial blind phase results provided confidence that many participants captured the transient progression of LOFWOS Test #13 well and that with further modeling improvement during the open phase, they could reduce discrepancies with the measured test data.

TABLE 1. SUMMARY OF BLIND PHASE PARTICIPATION

Organization	Abbreviation	Country	Submitted Transient Results?	Submitted Neutronics Results?
China Institute of Atomic Energy	CIAE	China	Yes	-
Institute of Nuclear Energy Safety Technology	INEST	China	Yes	Yes
North China Electric Power University	NCEPU	China	Yes	Yes
Xi'an Jiatong University	XJTU	China	Yes	-
French Alternative Energies and Atomic Energy Commission	CEA	France	Yes	-
Helmholtz-Zentrum Dresden-Rossendorf	HZDR	Germany	-	Yes
Karlsruhe Institute of Technology	KIT	Germany	Yes	Yes
Indira Gandhi Centre for Atomic Research	IGCAR	India	Yes	Yes
Nuclear and Industrial Engineering	NINE	Italy	Yes	-
Sapienza University of Rome	Rome	Italy	Yes	Yes
Japan Atomic Energy Agency	JAEA	Japan	Yes	Yes
Korea Atomic Energy Research Institute	KAERI	Republic of Korea	Yes	-
Nuclear Research and Consultancy Group	NRG	Netherlands	Yes	-
Nuclear Safety Institute of the Russia Academy of Sciences	IBRAE	Russia	-	-
Institute of Physics and Power Engineering	IPPE	Russia	Yes	Yes
Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas	CIEMAT	Spain	-	-
KTH Royal Institute of Technology	KTH	Sweden	-	Yes
Ecole Polytechnique Federale de Lausanne	EPFL	Switzerland	Yes	-
Paul Scherrer Institute	PSI	Switzerland	Yes	Yes
Argonne National Laboratory	ANL	US	Yes	Yes
Nuclear Regulatory Commission	NRC	US	-	-
Texas A&M University	TAMU	US	Yes	-
TerraPower	TP	US	-	-
Zachry Engineering	Zachry	US	Yes	-

Fig. 1 illustrates the total core power during LOFWOS Test #13 and the blind phase predictions for it. Total power is the sum of the measured fission power and the calculated decay heat. Agreement between the measured and predicted total power was reasonably good for most participants. Discrepancies during the first 200 seconds of the transient are likely due to the reactivity feedback responses predicted by each participant, with a nearly equal number of participants predicting fission power to decrease slightly faster or slightly slower than was measured during the actual test. Two participants predicted an insufficient amount of negative reactivity during the test to bring fission power down to or below decay heat levels by the end of the test.

Decay heat generation during LOFWOS Test #13 was calculated after the conclusion of the test based on the FFTF decay heat database, which incorporated the power history for the core assemblies, and the measured fission power. This data and the blind phase decay heat predictions are illustrated in Fig. 2**Error! Reference source not found.**.

Before the pumps tripped, all but one participant predicted a higher steady-state decay heat level than the measured data. During the transient, CRP participants predicted a relatively wider spread for decay heat than for fission power. All of the participants predicted a similar decay heat trend during the test, with predictions continuing to be larger than the calculated value throughout the test. By the end of the test, all but one participant predicted decay heat within a range of approximately 75% to 150% of the calculated end-of-test value. For some of these participants, excess fission power predicted at the end of the test is the likely reason for overpredicting decay heat.

Fig. 3 illustrates calculated and predicted net reactivity during the transient. Net reactivity was only calculated for the first three hundred seconds of the transients. The two most important reactivity feedbacks during the actual LOFWOS Test #13 transient were the negative GEM feedback and the positive Doppler feedback.

The large net reactivity decrease at the beginning of the test is primarily due to the negative reactivity from the GEMs. Discrepancies in the total worth of the GEM feedback predicted by the participants are responsible for much of the discrepancies with the calculated net reactivity. Most participants predicted a total GEM feedback of between negative $1 to negative $1.5, with one outlier predicting negative $2.4 for the GEM feedback.

As fission power decreased and the fuel cooled down, a large positive Doppler reactivity feedback was generated. For most participants, Doppler was the largest source of positive reactivity in their simulation. There was a very wide spread of Doppler predictions, ranging from nearly zero up to positive $1.2, with just over half of the participants' Doppler predictions in the vicinity of one dollar.

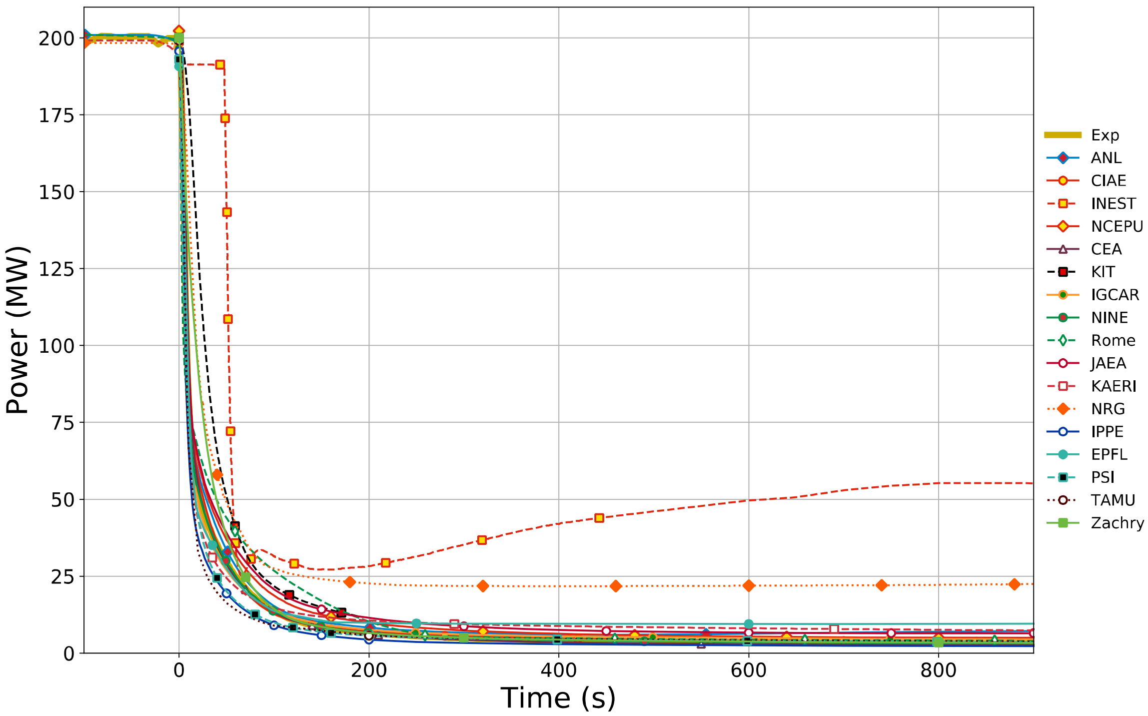

FIG. 1. Blind Phase Results - Total Power.

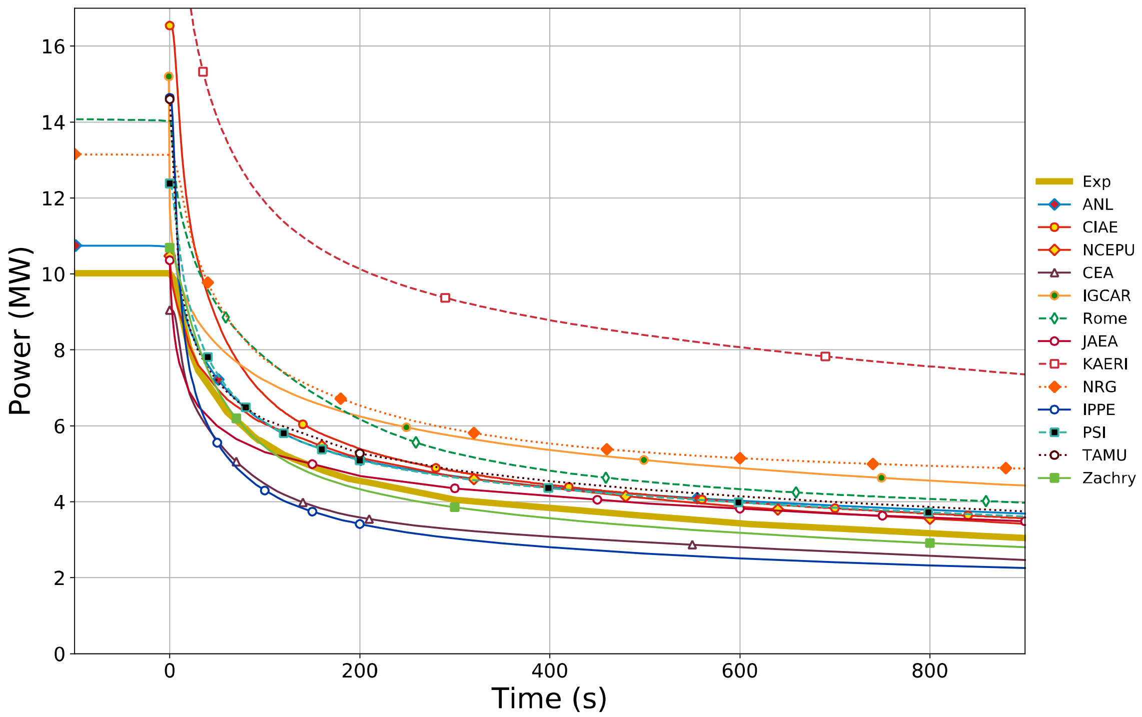

FIG. 2. Blind Phase Results – Decay Heat.

As the CRP progresses, discussions on the Doppler reactivity feedback are anticipated to focus on fuel-cladding gap conductance modeling, which is one of the most significant factors in the oxide fuel temperatures before and during the transient. Fig. 4 illustrates that there is a wide range of peak fuel temperatures predicted at steady-state. After 200s when core power had reduced to decay heat levels, most participants peak fuel temperature predictions were within a range of approximately 150°C. With a wider spread at the beginning of the transient, the varying changes in fuel temperatures predicted by the various participants helps explain the spread in the Doppler feedback prediction as well as the axial expansion feedback prediction.

The negative feedbacks from control rod driveline and radial core expansion will also likely be important discussion topics during the open phase. Radial core expansion in particular is one of the key modeling challenges for the CRP in that it can be a difficult to capture reactivity feedback effect and the codes used by some participants cannot represent the transient performance of FFTF's limited free bow core restraint system.

During the 1st Research Coordination Meeting (RCM) when the benchmark was first presented to the CRP participants, some participants expressed concern for being able to accurately model the FFTF pump based on the models available in their simulation codes. This is important for accurately predicting the transition to natural circulation. Fig. 5 illustrates the measured and predicted primary loop #1 mass flow rates during the transition to natural circulation. Almost all of the participants predicted a flow coastdown and transition to natural circulation that agrees very well with the measured test data. The agreement between the participants is consistent enough that the line for the measured test data is nearly obscured during the coastdown. Similar agreement was observed for primary loops #2 and #3. There is still some minor variation in the predictions immediately after the pumps trip. More than half of the participants predicted a slightly higher flow rate in the long-term in the three loops, but the low flow rates are where the measurements are most uncertain. Overall, the collective blind phase flow rate predictions are considered to be one of the biggest successes from the initial set of submissions.

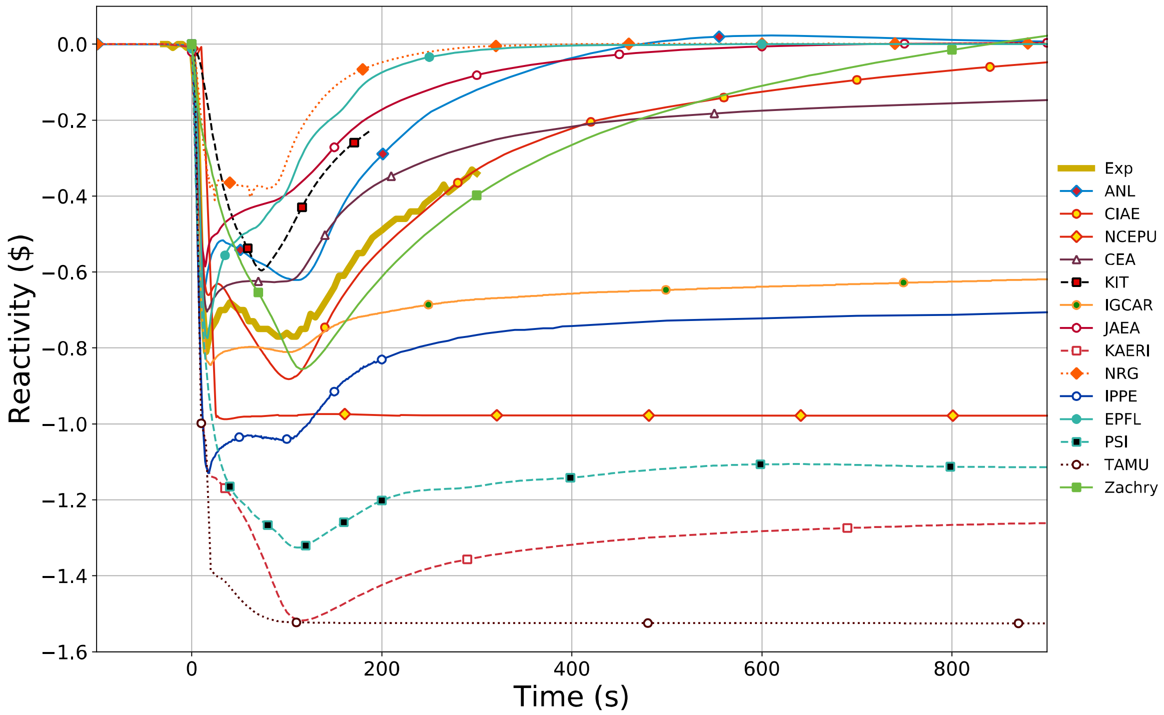

FIG. 3. Blind Phase Results – Net Reactivity.

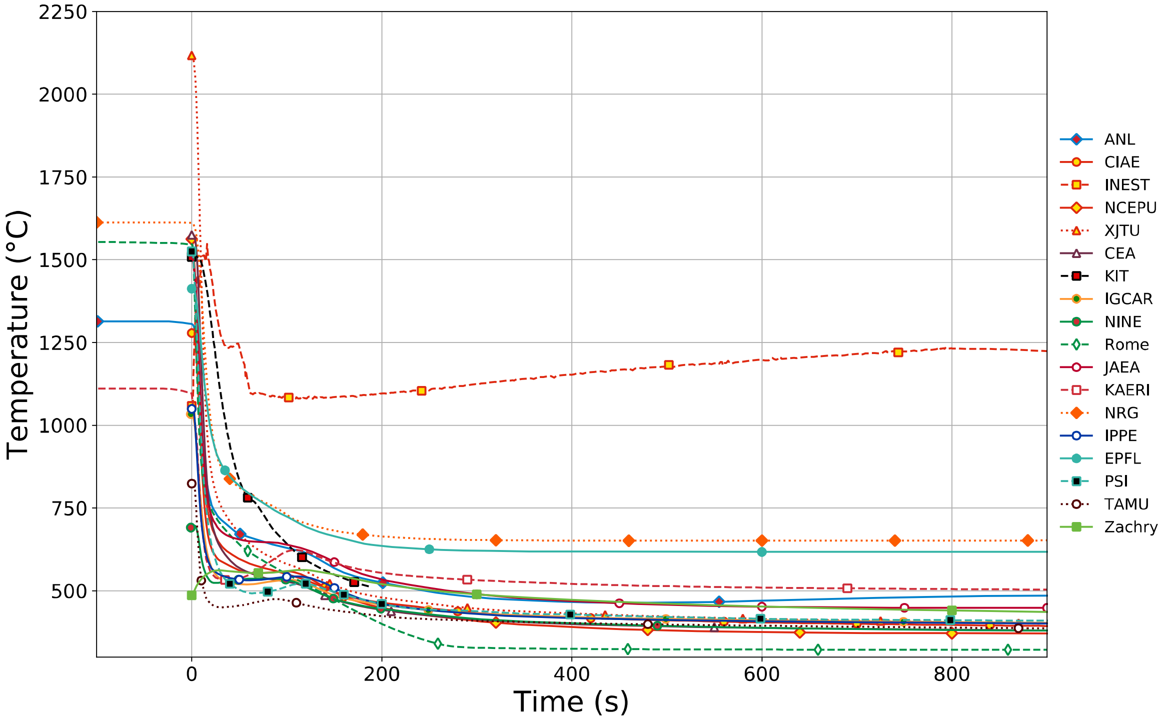

FIG. 4. Blind Phase Results – Peak Fuel Temperature.

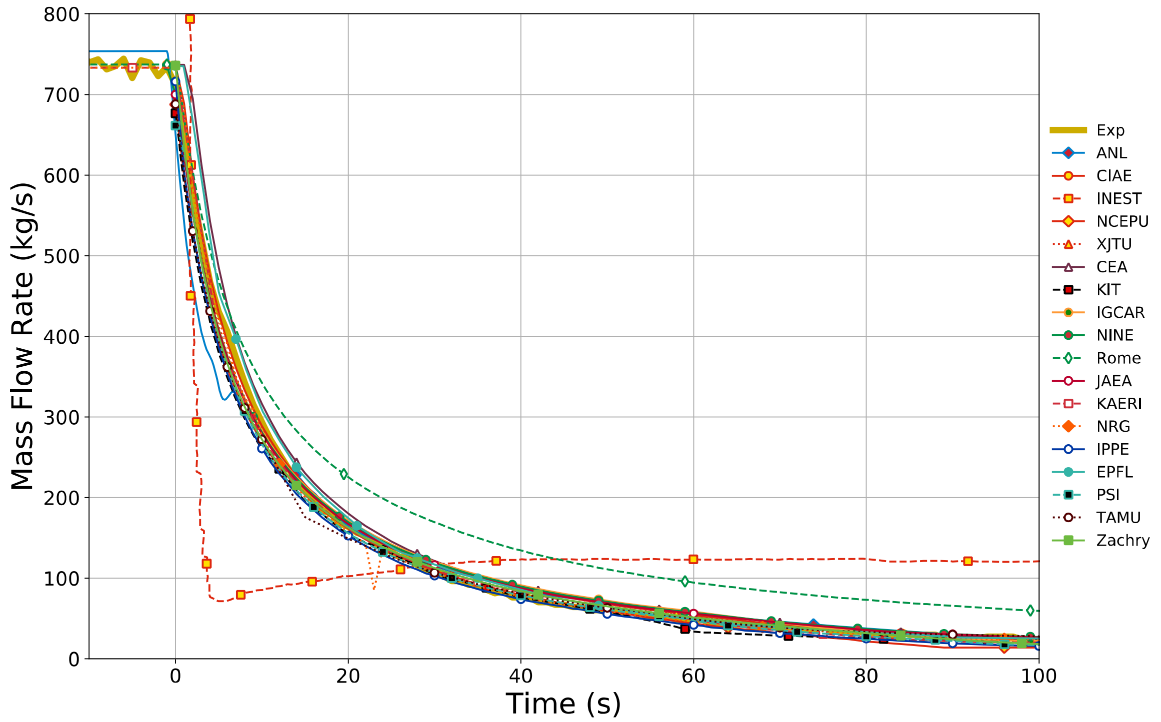

FIG. 5. Blind Phase Results – Primary Loop #1 Mass Flow Rate.

A number of parameters have been compared for the two fast response Proximity Instrumented Open Test Assemblies (PIOTA). The PIOTAs were special assemblies loaded with additional instrumentation to capture their performance during transients. The key instrumentation for the fast response PIOTAs installed for the LOFWOS tests were thermocouples at the assembly outlets. Fig. 6 and Fig. 7, present the coolant outlet temperatures from the Row 2 and Row 6 fast response PIOTAs, respectively. Additional comparisons are being performed for the blind phase predictions of the steady-state fuel, cladding, and coolant axial temperature distributions. These are not presented in the paper.

For the Row 2 PIOTA coolant outlet temperature, several participants' blind phase predictions agree very well with the measured test data. Smaller temperature increases were measured for the Row 6 PIOTA coolant outlet temperature, and fewer participants predicted this temperature with the same accuracy as for the Row 2 PIOTA. Most participants captured the initial rise in the coolant outlet temperatures and the subsequent drop due to the negative reactivity from the GEMs. After the GEMs had inserted all of their negative reactivity, temperatures gradually rose until reaching a peak due to the negative reactivity feedback from radial core expansion. Accurate predictions for power and natural circulation flow rates are essential for capturing these temperatures, especially in the long-term. Addressing these aspects of the various participants' models is expected to be a focus during the open phase of the CRP to improve agreement with the measured test data.

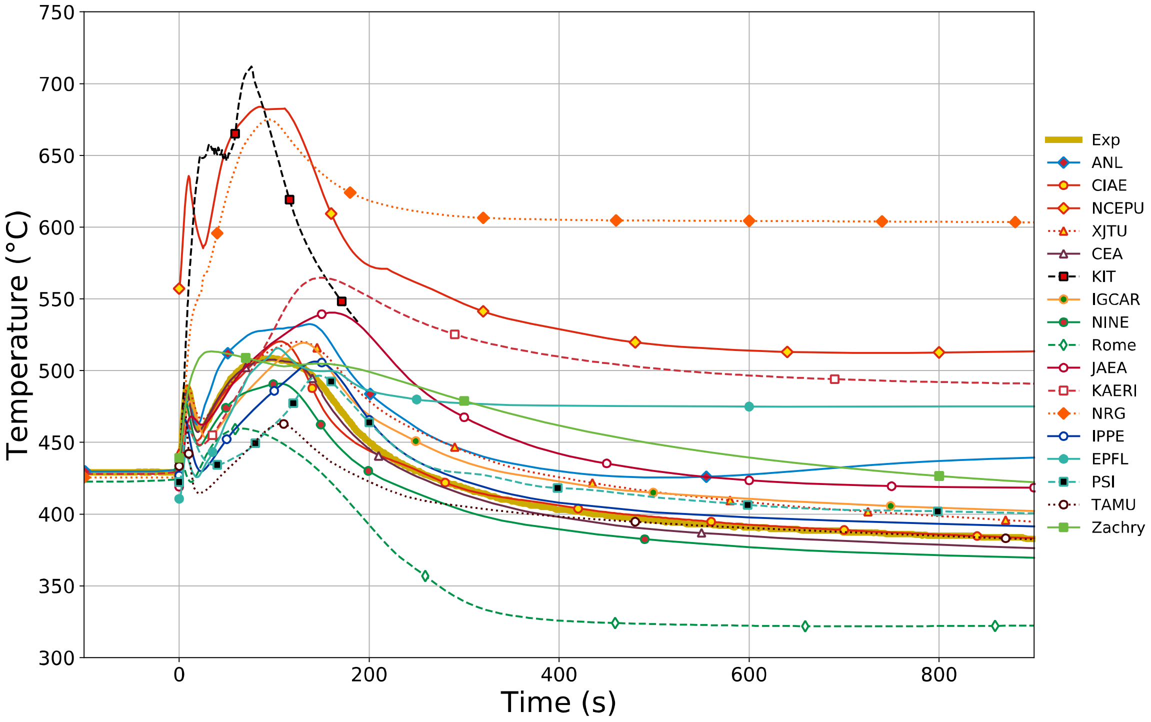

FIG. 6. Blind Phase Results – Row 2 PIOTA Coolant Outlet Temperature.

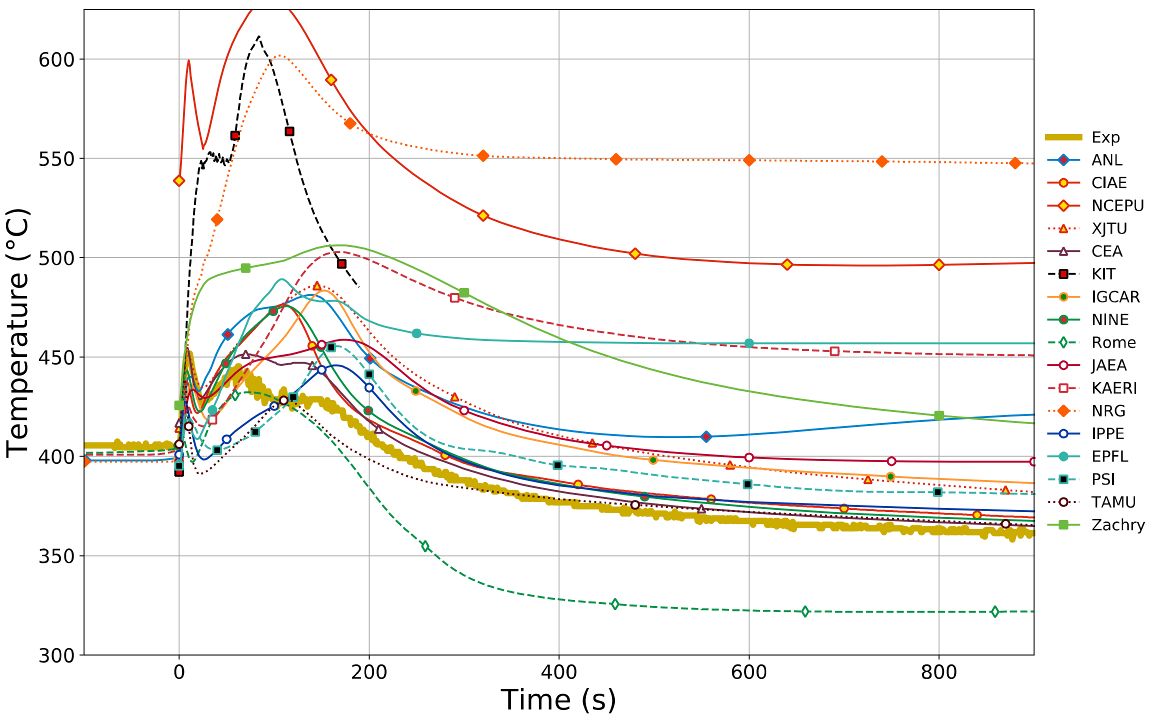

FIG. 7. Blind Phase Results – Row 6 PIOTA Coolant Outlet Temperature.

Fig. 8 illustrates the hot leg temperature predictions and measurement for primary loop #1. While the trend of the temperature evolution was well-captured for the PIOTA outlet temperatures, the trend of the temperature progression was not as well predicted for the primary loop hot leg temperatures. The measured data demonstrated relatively constant hot leg temperatures, representing the temperature of sodium discharging from the reactor vessel, while most participants predicted gradually increasing temperatures.

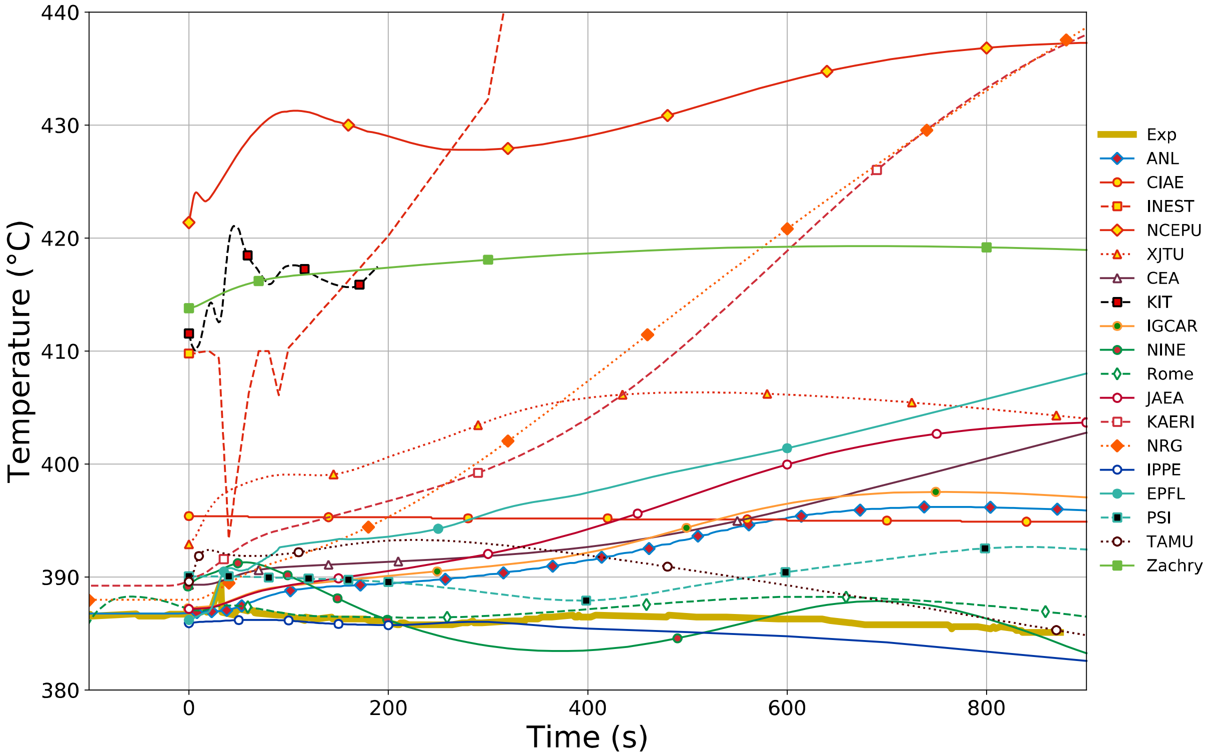

FIG. 8. Blind Phase Results - Primary Loop #1 Hot Leg Temperature.

4. SUMMARY

In 2018, the International Atomic Energy Agency established a coordinated research project for benchmark analysis of the Fast Flux Test Facility Loss of Flow Without Scram Test #13. Initiated at half power and full flow, LOFWOS Test #13 was an unprotected loss of flow without scram test that began when the three primary sodium pumps were tripped. The blind phase of the CRP concluded in October 2020. Results from the blind phase were evaluated for agreement with the measured test data and amongst collective participant results. For some parameters, many participants achieved relatively good agreement with the measured data while for other parameters, fewer participants successfully predicted the measurements. The initial blind phase results provide confidence that many participants captured the transient progression of LOFWOS Test #13 well and that with further modeling improvement during the open phase, discrepancies with the measured test data can be reduced.

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