THERMAL STRATIFICATION IN A POOL-TYPE GEOMETRY

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ABSTRACT

Sodium fast reactors are poised to be a leading candidate for the next generation of commercial reactor deployment. Before licensing can be completed it is important that information be gathered which examines reactor transients during loss of flow accidents. During loss of flow accidents thermally stratified layers can form in the reactor pool. The formation of thermal stratification in the primary pool of a sodium fast reactor during a loss of flow accident can cause cyclic thermal fatigue on the reactor vessel potentially leading to crack formation and weld failure. Computational models have been built to analyze the formation and persistence of thermal stratification during accident transients, but are not currently validated by experimental data. A thermal stratification research facility has been developed and tested to research thermal stratification with loss of flow type conditions. Data from the experiments will be used to validate computational models. The facility can simulate both protected and unprotected loss of flow accident transients in the temperature range of 200-325 [C] with flow rates from 2 gpm to 20 gpm.

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KEYWORDS
Thermal, Stratification, Hydraulics, Sodium, Experiment

1. INTRODUCTION

The pool-type sodium fast reactor (SFR) is a prominent design concept for generation IV nuclear reactors. In order to advance the scientific framework used to analyze SFR technology significant work must be completed to improve existing computational models used for reactor analysis. Specifically, there has been a demonstrated need for the advancement of computational models that predict thermal stratification behavior during reactor transients. Thermal stratification in the upper plenum of a pool type SFR can cause cyclic stress on the reactor vessel and potentially lead to mechanical failure. A reactor transient known to lead to thermal stratification in the upper plenum is a reactor trip [1]. This reactor trip can cause stratification to form in the reactor core (Fig. 1).

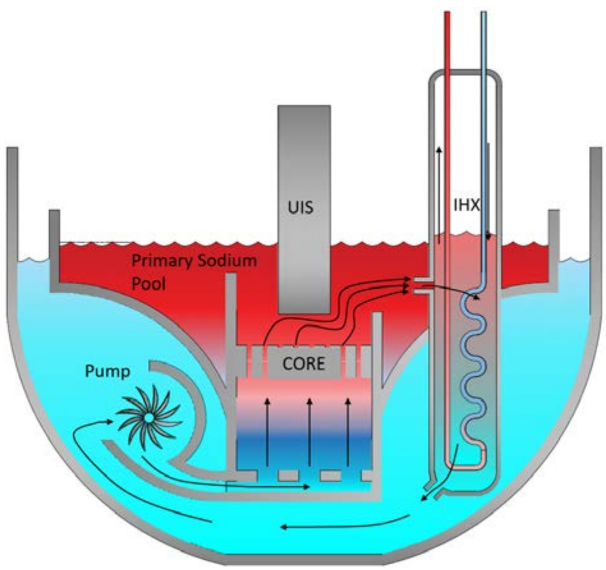

Figure 1: A schematic of thermal stratification that can exist in the reactor pool in the event of a reactor trip (Blue represents colder sodium and red represents hotter sodium; black arrows show the flow path of the primary coolant).

During a reactor trip one of the postulated events that must be considered is a loss of flow in the reactors primary coolant system. This loss of flow is considered either a protected or unprotected loss of flow (PLOF and ULOF). PLOF implies that the reactor successfully scrams. In the PLOF scenario a reactors core temperature is effectively lowered when the control rods are inserted into the core. This injects colder fluid from the reactor core into the hotter reactor pool potentially causing thermally stratified layers to form between the core and the inlet to the intermediate heat exchanger (IHX). In a ULOF scenario the reactor does not successfully scram and thus the core temperature immediately begins to rise. This temperature rise injects hotter fluid into a colder reactor pool causing unpredictable thermal mixing. The mixing of two different temperature fluids at the interface of the core exit and the reactor pool is known to cause thermal stratification throughout the reactor pool [2].

In order to predict the existence of thermal stratification a physics based computational model can be developed. This computational model must be validated by high fidelity experimental data. In order to obtain meaningful experimental data a facility has been designed and developed at the University of Wisconsin – Madison to study thermal stratification phenomena in large pools of sodium. Experimental data will be collected to support computational efforts from Massachusetts Institute of Technology (CFD) and Virginia Commonwealth University (system code). Work being conducted at these institutions will seek to examine large scale accident transients in SFR technology using computational and analytical models.

This thermal stratification research is specific to phenomena discovered in the hot pools of pool-type SFR designs. SFR designs like Argonne National Laboratory's (ANL) Advanced Burner Test Reactor (ABTR) have been analyzed with a system code for the occurrence of stratification [1]. However, this model has several shortcomings [3]. In order to improve upon this model so that it may be used to vet future reactor designs it must also be coupled with experimental data and computational fluid dynamic (CFD) code. Coupling the computational models with the experimental data that captures the thermal stratification will help to develop an efficient base model for predicting this phenomena.

2. Experimental Facility and Setup

A 264 L (70 gal.) liquid sodium research facility was designed and developed at the University of Wisconsin in 2017. This facility was specifically designed in order to observe the thermal stratification phenomena with high fidelity measurement techniques. This includes using fiber optic temperature measurement techniques in liquid sodium as well as electromagnetic flowmeters for velocity measurements in liquid sodium [4].

2.1. Experimental Design

In order to design an experiment capable of replicating conditions known to cause thermal stratification intensive design analysis needed to be carried out. It was integral for the success of the thermal stratification testing facility (TSTF) that the design be scaled to a well-documented Generation IV SFR design. Thus scaling analysis was carried out to determine the optimal size of the experimental facility such that meaningful data could be observed. The Advanced Burner Test Reactor (ABTR) designed by Argonne National Laboratory was selected for scaling analysis. Further information on the scaling of the test section of the TSTF to the ABTR can be found in a paper written by Schneider et al. in 2018 [5].

Scaling analysis of the ABTR produced the test section, shown in Figure 2, which was built as a component of the TSTF. This test section was designed to model the upper plena of a pool type fast reactor. The test section is designed such that there is an upper internal structure (UIS) inside of the test section similar to that of the upper plena of the ABTR. However, the current UIS in the test section of the TSTF is currently a solid blockage. The inlets to the test section are designed to inject sodium into the facility in a manner that would represent the effective cross sectional area of the scaled reactor core. The inlets were designed to be axisymmetric to the outlets such that during computational analysis of the test section there could be no use of a symmetry condition. Two different outlet heights are used to examine the effects of stratification as the primary coolant enters the IHX. Two heights were selected to accommodate for potentially different heights for an IHX inlet. This experimental design uses outlets at 1/3 and 2/3 of the overall height to examine this feature of a nuclear reactor.

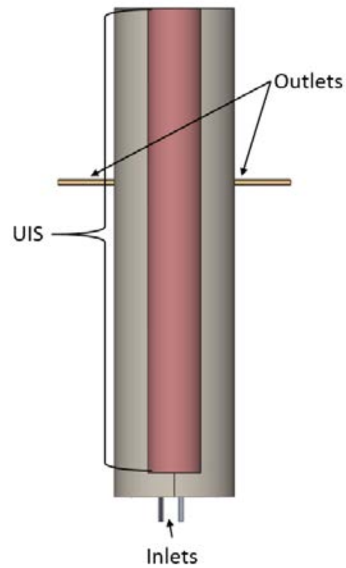

Fig. 2. Test Section inside of the TSTF.

2.2. Experimental Design Features

The culmination of the design and CFD analysis resulted in the development of Thermal Stratification Testing Facility (TSTF) (Fig. 3).

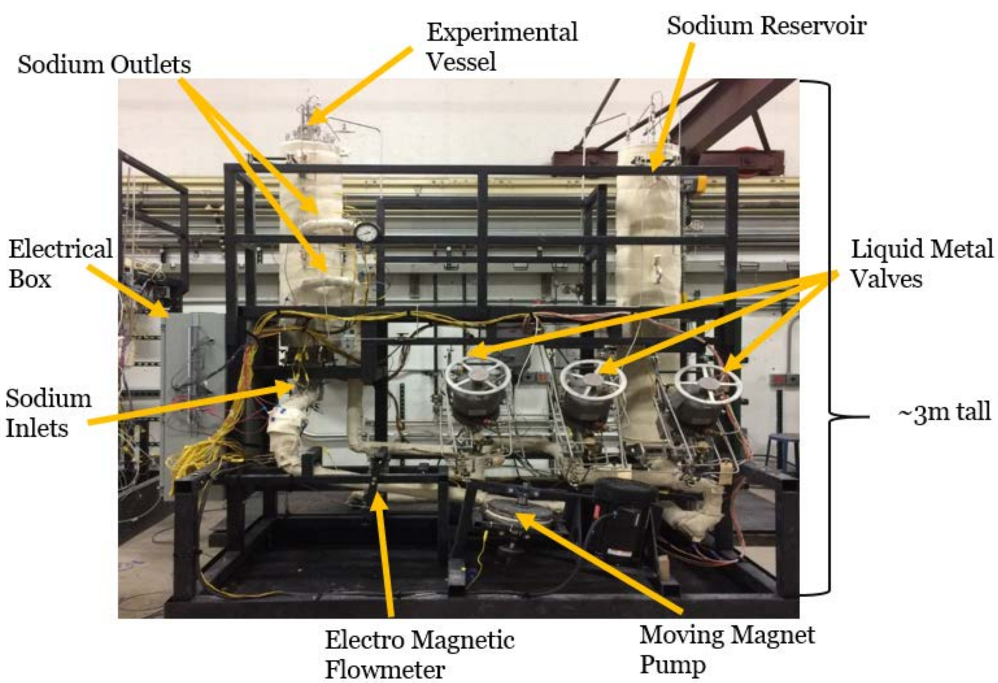

Figure 3: Thermal Stratification Testing Facility as of May 2018.

The TSTF was designed to be easily taken apart in order to accommodate the eventual replacement or removal of components such as the UIS. Having replaceable components allows for much flexibility in loop operation and variation of experimental parameters. The table below disseminates the experimental characteristics of the loop and its capabilities.

Table I. Experimental design characteristics of the TSTF.

Outlets	# of Inlets	UIS Height	UIS Diameter	DELTA T	Flow Rate
High or Low	2 or 3	0-0.11 [m]	0-0.14 [m]	0-100 (max temp. 325[C])	76 [lpm] 57 [lpm] 38 [lpm] 19 [lpm]

This table serves as the base for a test matrix that is used to develop numerous experimental campaigns. The two primary classes of experiments are the PLOF or ULOF experimental simulations. The experimental test section is configured with a UIS that can be translated along the vertical axis of the test section. There are three sodium inlets that resemble the core structure. One or two of these three jets can be blocked such to further the asymmetry of the flow. There are two physical outlets heights of the TSTF. One set of outlets are blocked while the other is in operation. Lastly, there are twelve thermocouples (TCs) evenly distributed throughout the active volume of the test section. Six TCs axially align with the outlets on the north side TCs (N. TCs) and the other six axially align with the south side TCs (S. TCs) of the test section.

The basic operation of this experimental facility, shown in Figure 4, is a four step process. First, the preheated loop (200 [C]) is filled with isothermal sodium from a 300 gallon sodium dump tank (not pictured) that is kept at 200 [C]. Then the sodium reservoir is isolated from the rest of the loop and brought up to the desired temperature. The primary closed sodium loop circulates sodium until the desired testing temperature difference is achieved between the primary loop and the sodium reservoir. During an experimental run the flow in the primary closed loop is stopped and an open loop persists allowing fluid to flow from the experimental reservoir, into the test section, and out of the test section back in to the 300 gallon dump tank (Fig. 4). Once all of the available sodium leaves the experimental reservoir the testing procedure is completed and the remainder of the sodium in the experiment is drained back into the dump tank.

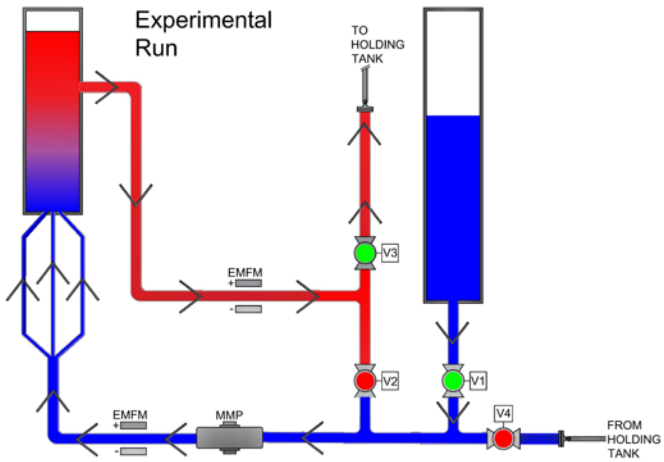

Figure 4: Operation of the TSTF during an experimental run.

3. RESULTS AND ANALYSIS

After the design and development of the TSTF testing campaigns immediately began. Initially time was taken to ensure proper function and safety of the TSTF. After initial shakedown testing was completed an experimental campaign began for initial PLOF test case scenarios (200 [C] into 250[C]). The following description of thermocouple locations and general experimental design are shown in Figure 5.

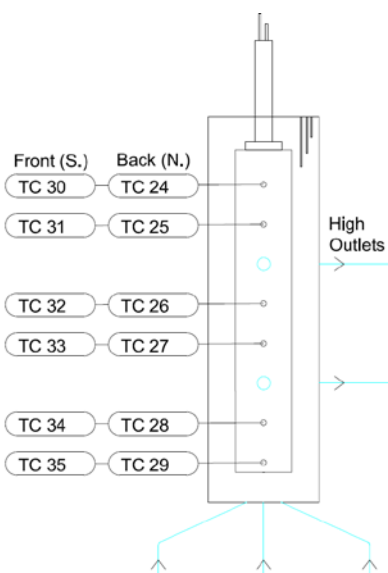

Figure 5: Layout of thermocouple location inside of the test section.

3.1. Initial Results and Tuning

The first noteworthy test was a 38 liters per minute [lpm] PLOF test where 200 [C] sodium was injected into a hotter 250 [C] pool (Fig 6). All reported thermocouple data is subjected to an error of ±1 [C]. These experimental Results show the thermocouple data for the PLOF scenario with the UIS not inserted inside of the experimental. The UIS was not put inside of the test section to allow for a simple understanding of the mixing behavior of sodium in a large pool. The fluid exited out of the high outlets. The experiment lasted 240 [s].

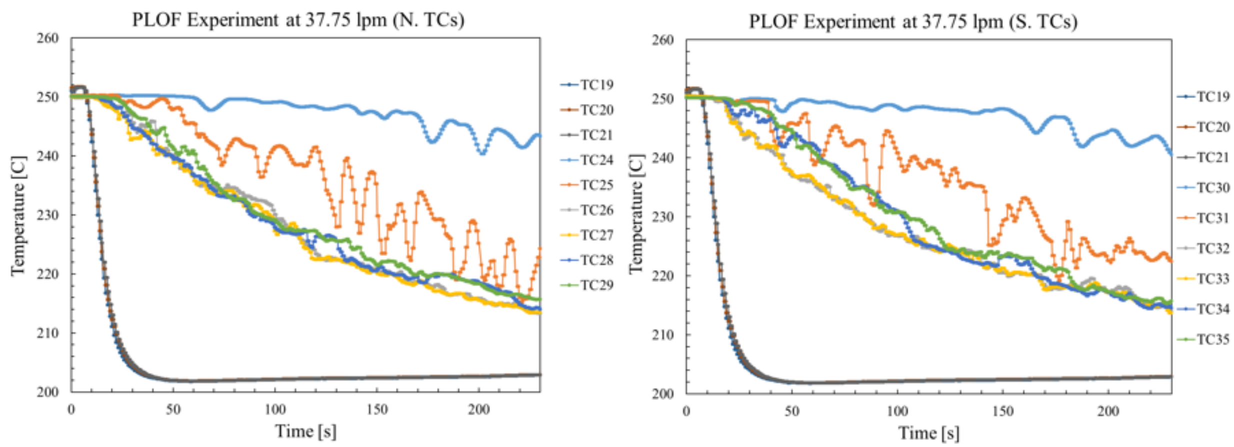

Figure 6: Initial experimental data from the TSTF.

After initial testing was completed and experimental capabilities were confirmed, data were compared to that of the computational model. The computational test was then modeled using a URANS simulation with an assumed turbulent Prandtl number of 0.9 (Fig. 7).

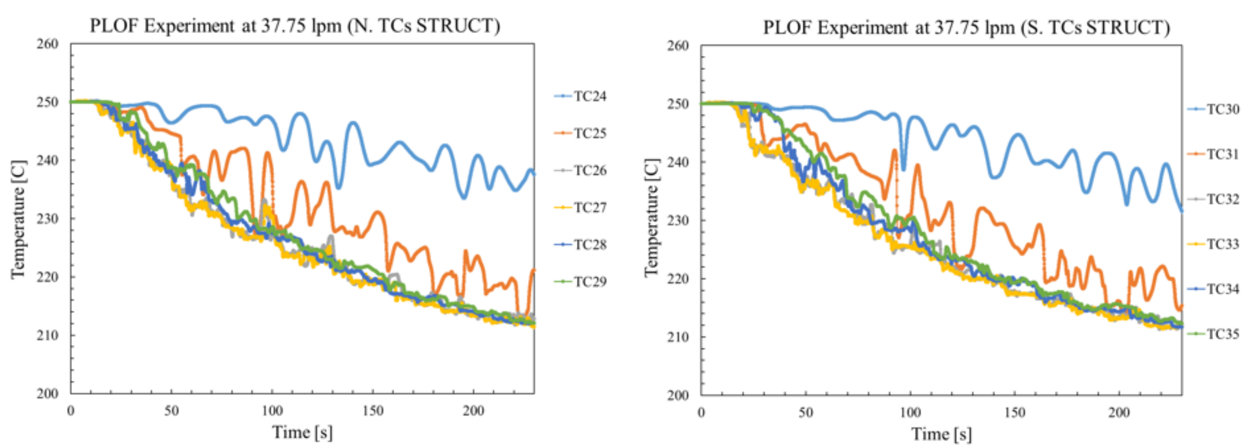

Figure 7: STRUCT analysis of the TSTF with associated experimental parameters.

A close relationship is observed between the computational and experimental data below the outlets. The top two thermocouples above the outlets (TC 24 and 30) show dissimilar behavior between experimental and computational data. There appears to be much larger fluctuations in temperature predicted by the

STRUCT model while the experimental data shows that TCs 24 and 30 lay over with less oscillations (Fig. 8).

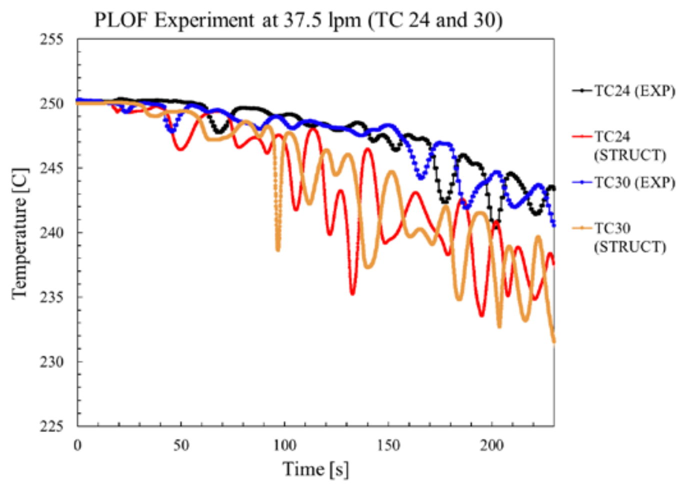

Figure 8: Comparison of experimental and computational (STRUCT) data.

This comparison shows good correlation between experimental data and computational analysis. This comparison of data will continue to be developed upon in future testing campaigns with the UIS inserted into the test section. The experimental data above was collected by thermocouples and will be directly compared to data collected by fiber optic temperature sensors in future experiments. The fiber optic temperature sensors are strung axially at three different locations in the system (Fig. 9).

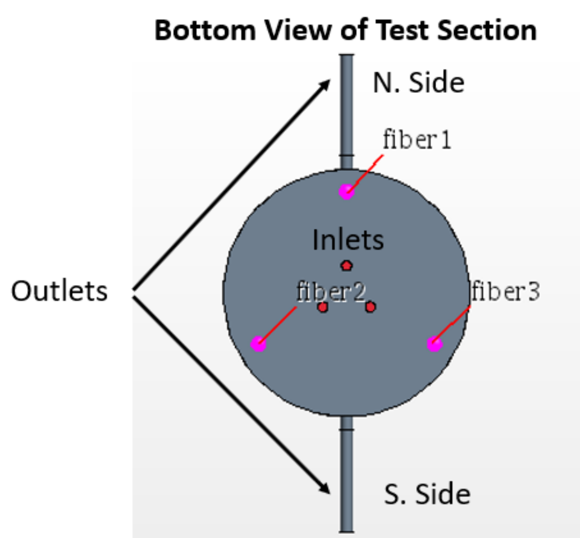

Figure 9: Bottom view of test section showing TC and Fiber locations.

A mesh sensitivity studied was carried out to determine the effect of the mesh density on the experimental results. Three different meshes were used to analyze the computational simulation (Table II).

Table II. CFD mesh analysis

Mesh	Cell Number
Coarse	253589
Medium	321006
Dense	411478

The differences in the mesh size had little to no bearing over the results of the simulation (Fig. 10).

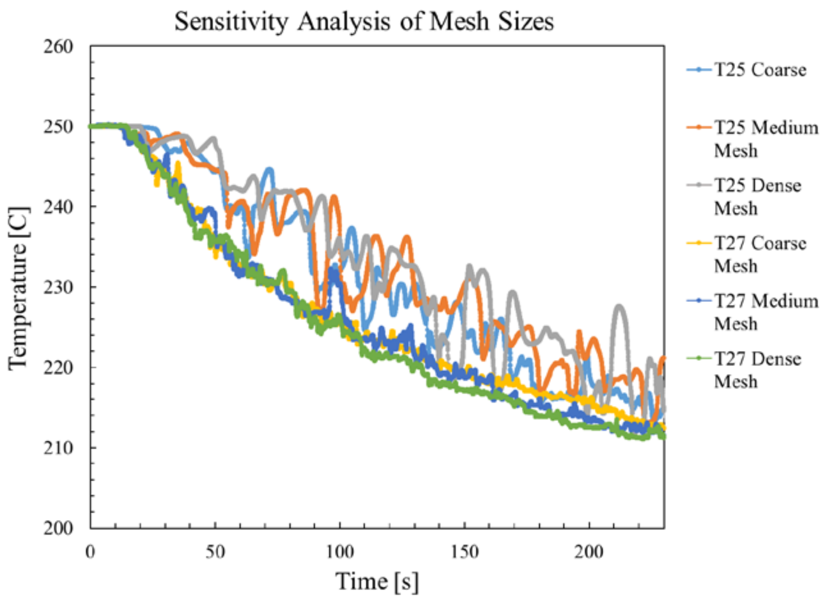

Figure 10: Bottom view of test section showing TC and Fiber locations.

3.2. Future Testing Campaigns

Once significant testing has been conducted on the flow of sodium inside of the tank without the UIS, the UIS will then be inserted into the test section. Once the UIS is inserted back into the test section testing will again commence for a broad range of ULOF and PLOF scenarios. After that a series of test will be conducted to simulate special case scenarios. Special cases will consist of rerunning tests but for a UIS geometry that is more consistent with common UIS designs. Another potential test will be to simulate a flow coast down scenario for both the ULOF and PLOF scenarios, instead of having a constant flow inlet. This scenario is more consistent with what is observed in a full scale nuclear reactor loss of flow accident transient. Finally, specific tests will be conducted in order to aid the computational groups in their efforts to create a CFD and systems code analysis of thermal stratification in the upper plena of large pool-type geometries.

4. CONCLUSIONS

Testing campaigns are underway in the liquid sodium thermal stratification testing facility. Analyzing the development of thermal stratification using high fidelity fiber optic temperature sensors will allow for an intimate understanding of the mixing associated with PLOF and ULOF accident scenarios. Understanding mixing behavior during these simulated transients will provide a detailed form of validation for computational models used to simulate these transients. It is of great importance for the future of SFR technology, and other Generation IV reactor technologies alike, that accurate computational models be developed. Accurate computational models be used for large scale simulations when creating an experiment is not feasible. The TSTF will continue to be used for analyzing SFR related accident transients in order to validate both CFD and system code models.

NOMENCLATURE (IF NEEDED)

TSTF = Thermal Stratification Testing Facility
CFD = Computational Fluid Dynamics
ABTR = Advanced Burner Test Reactor
ULOF = Unprotected Loss of Flow
PLOF = Protected Loss of Flow
UIS = Upper Internal Structure
SFR = Sodium Fast Reactor
IHX = Intermediate Heat Exchanger
TCs = Thermocouples

ACKNOWLEDGMENTS

The authors would like to thank the Department of Energy, Nuclear Energy University Programs (DOE-NEUP) for support under NU-16-UWM-030301-12 project 16-10268 “Sodium cooled fast reactor key modeling and analysis for commercial deployment”.

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