INL/MIS-22-67879-Revision-0

Ongoing Data Platform Development for High-Temperature Gas-cooled Reactor (HTGR) Thermal-Fluid Experiments Supported by Nuclear Energy University Program (NEUP) [Presentation Slides]

Changing the World's Energy Future

Sunming Qin, Minseop Song

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Ongoing Data Platform Development for HTGR Thermal-Fluid Experiments Supported by NEUP

DOE-NE Advanced Reactor Technologies (ART)
2022 Gas-Cooled Reactor (GCR) Program Review Meeting

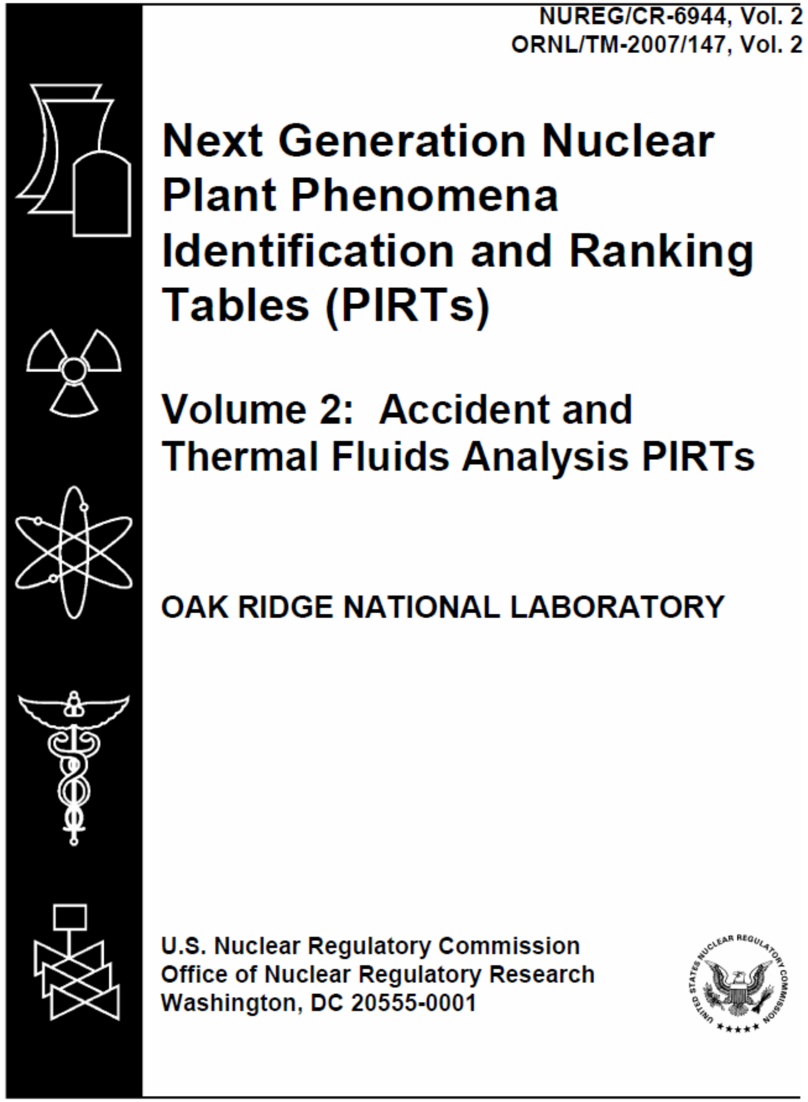
ART Advanced Reactor Technologies
GAS-COOLED REACTORS

Introduction

- There are in total 30 NEUP [1] projects focusing on the thermal-fluid experiments related with High-Temperature Gas-cooled Reactor (HTGR) from FY2009 to FY2021, producing **a large amount of high-quality validation data**, however,
  - data is distributed at universities and *has not been disseminated to the HTGR community well*,
  - final reports are now only available on the OSTI webpage.
  - This is a missed opportunity for the HTGR research community needing code validation data.
- Our goal is aimed to improve access to the HTGR validation data and optimize the return on the significant investment made by DOE. Supported by the Advanced Reactor Technologies (ART) Gas-Cooled Reactor (GCR) program [2], we conducted a survey to:
  - **Assess completed and ongoing HTGR NEUP projects,**
  - **With the aim to develop a public-accessible data platform** that can be used to retrieve code validation data and guide future NEUP investments.

Background – HTGR PIRT Study

- An accident and thermal-fluids phenomena identification and ranking process was conducted by a panel of experts [5] on the next generation nuclear plant (NGNP) designs, considering both pebble-bed and prismatic gas-cooled reactor configurations.
- Some of the common and most highly-ranked event scenarios for both prismatic and pebble-bed HTGR designs have been identified as:
  - Pressurized loss of forced cooling (PLOFC);
  - Depressurized loss of forced cooling (DLOFC);
  - Air ingress following the DLOFC;
  - Steam/water ingress;
  - Anticipated transients without scram (ATWS), etc.



NUREG/CR-6944, Vol. 2
ORNL/TM-2007/147, Vol. 2

Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)

Volume 2: Accident and Thermal Fluids Analysis PIRTs

OAK RIDGE NATIONAL LABORATORY

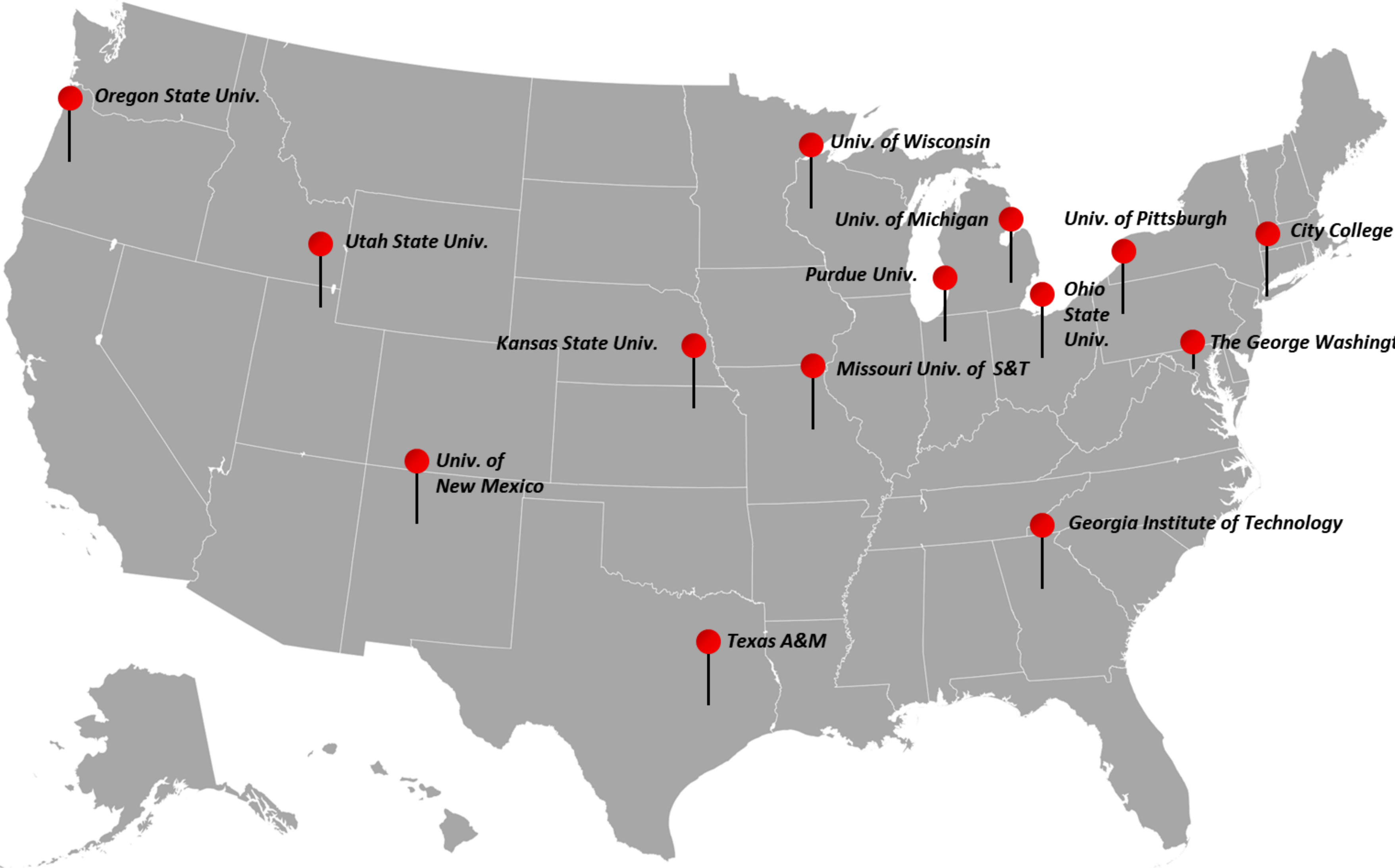
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

NEUP-HTGR Projects Overview

Advanced Reactor Technologies
GAS-COOLED REACTORS

Project No.	Project Name	Project Instructors and Affiliation
09-764	An innovative and advanced coupled neutron transport and thermal hydraulic method (Tool) for the design, analysis and optimization of VHTR NGNP Prismatic Reactor	Rahnema, Farzad (Georgia Institute of Technology)
09-771	Creation of a Full-core HTR Benchmark with the Fort St. Vrain Initial Core and Assessment of Uncertainties in the FSV Fuel Composition and Geometry	Martin, William (University of Michigan)
09-784	Investigation of Countercurrent Helium-air Flows in Air-ingress Accidents for VHTRs	Sun, Xiaodong (Ohio State University)
09-817	CFD Model Development and Validation for High Temperature Gas Cooled Reactor Cavity Cooling System (RCCS) Applications	Hassan, Yassin (Texas A&M University)
09-830	Graphite Oxidation Simulation in HTR Accident Conditions	Mohamed El-Genk (University of New Mexico)
09-840	Investigation on the Core Bypass Flow in a Very High Temperature Reactor	Hassan, Yassin (Texas A&M University)
11-3079	Thermal-hydraulic analysis of an experimental reactor cavity cooling system with air	Michael Corradini (University of Wisconsin)
11-3080	Critical Heat Flux Phenomena at High Pressure and Low Mass Fluxes	Michael Corradini (University of Wisconsin) - Part 1: Experiments Qiao Wu (OSU Co-PI) and Jeff Luitjens - Part 2: Modeling
11-3081	Transient mixed convection validation for NGNP	Barton Smith (Utah State University)
11-3218	Experimental Investigation of Convection and Heat Transfer in the Reactor Core for a VHTR	Masahiro Kawaji (City College of New York)
12-3582	Experimentally Validated Numerical Models of Non-isothermal Turbulent mixing in High Temperature Reactors	Mark L. Kimber (University of Pittsburgh)
12-3759	Experimental and CFD Studies of Coolant Flow Mixing within Scaled Models of the Upper and Lower Plenum of a NGNP Gas-Cooled Reactors	Hassan, Yassin (Texas A&M University)
13-4884	Validation data for depressurized and pressurized conduction cooldown, validation data acquisition in HTTF during PCC events	Philippe M Bardet (The George Washington University)
13-4953	Experimental and Computational Investigations of Plenum-to-Plenum Heat Transfer and Gas Dynamics under Natural Circulation in a Prismatic Very High Temperature Reactor	Muthanna Al-Dahhan (Missouri University of Science & Technology)
13-5000	Model Validation using novel CFD-grade experimental database for NGNP Reactor Cavity cooling systems with water and air	Annalisa Manera (University of Michigan)
14-6435	Fluid stratification separate effects analysis, testing and benchmarking	Andrew C. Klein (Oregon State University)
14-6786	Experimental Investigation and CFD Analysis of Steam Ingress Accidents in HTGRs	Xiaodong Sun -> Richard Christensen (Ohio State University)
14-6794	scaling Studies for Advanced High Temperature Reactor Concepts	Brian Woods (Oregon State University)
15-8205	Experimental investigation of forced convection and natural circulation cooling of a vhtr core under normal operation and accident scenarios	Masahiro Kawaji (City College of New York)
15-8627	Experimental validation data and computational models for turbulent mixing of bypass and coolant jet flows in gas-cooled reactors	Mark Kimber (University of Pittsburgh)
16-10244	Integral System Testing for Prismatic Block Core Design HTGR	Brian Woods (Oregon State University)
16-10509	CFD and system code benchmark data for plenum-to-plenum flow under natural, mixed and forced circulation conditions	Barton Smith (Utah State University)
17-13115	Experimental Determination of Helium Air Mixing in Helium Cooled Reactor	Victor Petrov (University of Michigan)
18-15058	High-resolution experiments for extended LOFC and Steam Ingress Accidents in HTGRs	Xiaodong Sun (University of Michigan)
19-17037	Investigation of HTGR Reactor Building Response to a Break in Primary Coolant Boundary	Shripad T. Revankar (Purdue University)
19-17183	Mixing of helium with air in reactor cavities following a pipe break in HTGRs	Masahiro Kawaji (City College of New York)
20-20074	Characterization of Plenum to Plenum Natural circulation flows in a high temperature gas reactor (HTGR)	Masahiro Kawaji (City College of New York)
21-24104	Thermal Hydraulics Investigation of Horizontally Oriented Layout micro HTGRs Under Normal Operation and PCC Conditions Using Integrated	Muthanna H. Al-Dahhan (Missouri University of Science and Technology)
21-24111	Experimental Investigations of HTGR Fission Product Transport in Separate-effect Test Facilities Under Prototypical Conditions for Depressurization and Water-ingress Accidents	N.K. Anand (Texas A&M University)
21-24287	Investigating Heat Transfer in Horizontally Oriented HTGR under normal and PCC conditions	Hitesh Bindra (Kansas State University)

NEUP-Related HTGR Projects – Universities Participated



List of NEUP-Related HTGR Projects

UNIVERSITY PARTICIPATING IN NEUP

FINISHED NEUP PROJECT # in RED

ONGOING NEUP PROJECTS # in BLUE

University	Finished NEUP projects (red)	Ongoing NEUP projects (blue)
Georgia Institute of Technology	09-764	
University of Michigan	09-771, 17-13115, 13-5000	18-15058
Ohio State University	09-784, 14-6786	
Texas A&M University	09-817, 12-3759, 09-840	21-24111
University of New Mexico	09-830	
University of Wisconsin	11-3079, 11-3080	
Utah State University	11-3081, 16-10509	
City College of New York	11-3218, 15-8205	19-17183, 20-20074
University of Pittsburgh	12-3582, 15-8627	
The George Washington University	13-4884	
Missouri University of S&T	13-4953	21-24104
Oregon State University	14-6435, 14-6794, 16-10244	
Purdue University		19-17037
Kansas State University		21-24287

Thermal-Fluid Phenomena and Operating/Accident Scenario – Studied in NEUP HTGR Projects

- **Thermal-Fluid Phenomena**
  - Plenum Mixing / Jet Impingement
    - Lower plenum
    - Upper plenum
    - Plenum to plenum
  - Ingress
    - Air ingress
    - Steam/Water ingress
  - Conjugate Heat Transfer
    - Forced convection
    - Natural convection
  - Natural Convection in RCCS
  - Bypass Flow
  - Fluid Stratification
  - Nuclear-related (decay heat, fission product, etc.)

- **Various Scenarios**
  - Normal Operation
  - Pressurized loss of forced cooling (PLOFC);
  - Depressurized loss of forced cooling (DLOFC);
  - Load Change (Transient)
  - Steam Generator Accident

Thermal-Fluid Phenomena and Accident Scenario – Database Matrix

FINISHED NEUP PROJECT # in RED
ONGOING NEUP PROJECTS # in BLUE

PHENOMENA			SCENARIOS				
			NORMAL OPERATION	PRESSURIZED LOSS OF FLOW	DEPRESSURIZED LOSS OF FLOW	LOAD CHANGE (TRANSIENT)	STEAM GENERATOR TUBE BREAK
PHENOMENA	PLENUM MIXING / JET IMPINGEMENT	LOWER PLENUM	12-3582 15-8627	16-10244	16-10244		
		UPPER PLENUM	12-3759	18-15058	18-15058	13-5000	
		PLENUM TO PLENUM	13-4953 16-10509	20-20074	20-20074		
	INGRESS	AIR INGRESS		15-8205	09-784 13-4884 14-6435 15-8205 17-13115		14-6786 19-17183
		STEAM/WATER INGRESS		18-15058	18-15058 21-24111		14-6786

Thermal-Fluid Phenomena and Accident Scenario – Database Matrix (Cont'd)

FINISHED NEUP PROJECT # in RED

ONGOING NEUP PROJECTS # in BLUE

PHENOMENA		SCENARIOS: NORMAL OPERATION	SCENARIOS: PRESSURIZED LOSS OF FLOW	SCENARIOS: DEPRESSURIZED LOSS OF FLOW	SCENARIOS: LOAD CHANGE (TRANSIENT)	SCENARIOS: STEAM GENERATOR TUBE BREAK
CONJUGATE HEAT TRANSFER (CORE)	FORCED CONVECTION	09-771, 11-3081, 16-10509, 21-24104, 21-24287	11-3218, 21-24104, 21-24287	11-3218		
CONJUGATE HEAT TRANSFER (CORE)	NATURAL CONVECTION	14-6794, 16-10509	14-6794	14-6435		
NATURAL CONVECTION IN RCCS		09-817, 11-3079, 13-4953			09-817, 11-3079, 13-5000	
BYPASS		09-830, 15-8627	15-8205	09-840, 15-8205		
FLUID STRATIFICATION				14-6435		
NUCLEAR (DECAY HEAT, REACTIVITY FEEDBACK, FISSION PRODUCT, ETC.)		09-764, 11-3080		19-17037, 21-24111		

FINISHED NEUP PROJECT # in RED

ONGOING NEUP PROJECTS # in BLUE

PHENOMENA			SCENARIOS: NORMAL OPERATION	PRESSURIZED LOSS OF FLOW	DEPRESSURIZED LOSS OF FLOW	LOAD CHANGE (TRANSIENT)	STEAM GENERATOR TUBE BREAK
PHENOMENA	PLENUM MIXING / JET IMPINGEMENT	LOWER PLENUM	12-3582 15-8627	16-10244	16-10244		
		UPPER PLENUM	12-3759	18-15058	18-15058	13-5000	
		PLENUM TO PLENUM	13-4953 16-10509	20-20074	20-20074		
	INGRESS	AIR INGRESS		15-8205	09-784 13-4884 14-6435 15-8205 17-13115		14-6786 19-17183
		STEAM/WATER INGRESS		18-15058	18-15058 21-24111		14-6786
	CONJUGATE HEAT TRANSFER (CORE)	FORCED CONVECTION	09-771 11-3081 16-10509 21-24104 21-24287	11-3218 21-24104 21-24287	11-3218		
		NATURAL CONVECTION	14-6794 16-10509	14-6794	14-6435		
	NATURAL CONVECTION IN RCCS		09-817 11-3079 13-4953			09-817 11-3079 13-5000	
	BYPASS		09-830 15-8627	15-8205	09-840 15-8205		
	FLUID STRATIFICATION				14-6435		
	NUCLEAR (DECAY HEAT, REACTIVITY FEEDBACK, FISSION PRODUCT, ETC.)		09-764 11-3080		19-17037 21-24111		

Urgent Need for NEUP-HTGR Data Platform

- NEUP projects have produced valuable results with both computational and experimental studies, but detailed information is not always available, including:
  - Detailed facility description;
  - Instrumentation locations;
  - Boundary conditions;
  - Resulting experimental data (raw/processed), etc.
- It is crucial and urgent to construct a more transparent, sustainable, and equitable process for the community to harvest important HTGR thermal fluid validation data created with U.S. taxpayer funding.
  - ART-GCR program will create a central data platform at INL to *identify, organize and store* the results of these valuable research projects, and
  - provide future guidance for storage and transmission of important project documentations for later NEUPs.

NEUP Database Example – Project No. 11-3081

- The Utah State University team conducted their experiments using a Rotatable Wind Tunnel (RoBuT) to establish high-quality validation data for vertical plate heat convection.
- Available publicly at: https://digitalcommons.usu.edu/all_datasets/8/

Experimental Validation Data for CFD of Steady and Transient Mixed Convection on a Vertical Flat Plate

Download

Blake W. Lance, Utah State University

Description

Simulations are becoming increasingly popular in science and engineering. One type of simulation is Computation Fluid Dynamics (CFD) that is used when closed forms solutions are impractical. The field of Verification & Validation emerged from the need to assess simulation accuracy as they often contain approximations and calibrations.

Validation involves the comparison of experimental data with simulation outputs and is the focus of this work. Errors in simulation predictions may be assessed in this way. Validation requires highly-detailed data and description to accompany these data, and uncertainties are very important.

The purpose of this work is to provide highly complete validation data to assess the accuracy of CFD simulations. This aim is fundamentally different from the typical discovery experiments common in research. The measurement of these physics was not necessarily original but performed with modern, high fidelity methods. Data were tabulated through an online database for direct use in Reynolds-Averaged Navier Stokes simulations. Detailed instrumentation and documentation were used to make the data more useful for validation. This work fills the validation data gap for steady and transient mixed convection.

The physics in this study included mixed convection on a vertical flat plate. Mixed convection is a condition where both forced and natural convection influence fluid momentum and heat transfer phenomena. Flow was forced over a vertical flat plate in a facility built for validation experiments. Thermal and velocity data were acquired for steady and transient flow conditions. The steady case included both buoyancy-aided and buoyancy-opposed mixed convection while the transient case was for buoyancy-opposed flow. The transient was a ramp-down flow transient, and results were ensemble-averaged for improved statistics. Uncertainty quantification was performed on all results with bias and random sources.

ADDITIONAL FILES

Data.zip (13053 kB)
MD5: 0206abc512b00edfd182e3c30988678b

Aid-BC-AtmCond.csv (1 kB)
MD5: d4db291e275912d746eca81b9cfb13cd

Aid-BC-HeatedWallTemp.csv (7 kB)
MD5: 5395739959ed9d4af353d8abdeddef98

Aid-BC-InletTemp.csv (1 kB)
MD5: 44387a1b86698be28256022ea987bbe6

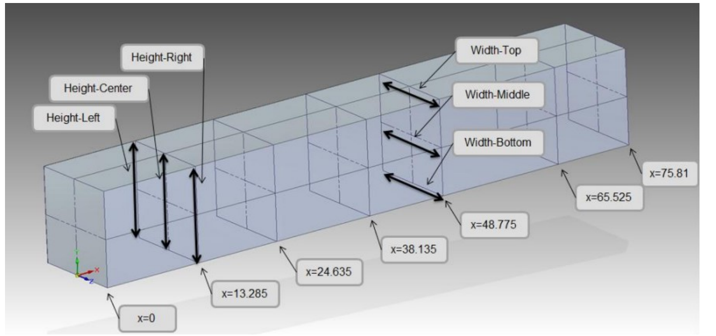
Aid-BC-Inlet-Vel.csv (270 kB)
MD5: c4388b1857a7273be3c0d7d3b81a2c53

Aid-BC-LeftWallTemp.csv (1 kB)
MD5: 5065ed2943a7005e7345051664f7ed4d

Aid-BC-RightWallTemp.csv (1 kB)
MD5: a5107835afb25b406dae12bdf81a1fa8

Aid-BC-TopWallTemp.csv (1 kB)

- CAD file (.x_t)
- Geometry description
- Experimental data (.csv)
- Matlab file for analysis



A	B	C	D	E	F	G
X	Y	Z	T[K]	B_T[K]	S_T[K]	U_T[K]
0	0	-0.14	327.6	1	0.4034	1.078
0	0	-0.07	334.5	1	0.4393	1.092
0	0	0	340.3	1	0.4762	1.108
0	0	0.07	339.3	1	0.4342	1.09
0	0	0.14	336.7	1	0.4152	1.083
0.014	0	-0.152	329.7	1	0.7218	1.233
0.014	0	-0.138	395.6	1	0.06317	1.002
0.014	0	-0.07	399.4	1	0.05842	1.002
0.014	0	0	400.9	1	0.05291	1.001
0.014	0	0.07	398.7	1	0.05744	1.002
0.014	0	0.138	394.3	1	0.06825	1.002
0.014	0	0.152	327	1	0.7986	1.28
0.043	0	-0.152	339	1	0.7688	1.261
0.043	0	-0.138	397	1	0.06488	1.002
0.043	0	-0.07	400.4	1	0.05744	1.002
0.043	0	0	402	1	0.05004	1.001
0.043	0	0.07	399.7	1	0.05489	1.002
0.043	0	0.138	395.4	1	0.06553	1.002
0.043	0	0.152	334.6	1	0.9964	1.412
0.074	0	-0.152	342.3	1	0.8051	1.284
0.074	0	-0.138	399.4	1	0.06191	1.002

ConductionAnalysis2.m

```
%
% Blake Lance
% 21 January 2014
% Version 2, Blake Lance, 20 July 2015
%   Updated with flosser TC Probe geometry and data

%% Initialize
tic;

HFS = 1;    % Which HFS location in x to use
Ny = 201;   % Number of discretized nodes in the lead section
Nz = 100;   % Number of points in the z-direction to plot
% omega = 1;    % Relaxation factor
y_TC = 0.0; % The y location of the thermocouple sensor [mm] (doesn't have to be at wall)
T_b = 100;  % Guess the temperature of the corner [deg C] (temperature of the base)
Case = 'Mixed';    % The case to test with experimental velocity and temperature profiles
% Case = 'Forced';    % The case to test with experimental velocity and temperature profiles

k_chromel = 18.6;   % Thermal conductivity of chromel [W/mK]
k_alumel = 31;      % Thermal conductivity of alumel [W/mK]
k_TC = k_alumel;    % Choose the thermal conductivity to use
D = 5.08E-2;        % Diameter of TC wire [mm] (0.002 in)
L_lead = 22.86;     % Length of lead wire [mm] (0.9 in)
% L_lead = 40;      % Length of lead wire [mm] (1 in)
% L_sensor = 6.35;    % Length from TC junction to corner [mm] (1/4 in)
% L_sensor = 3.58;    % Length from TC junction to corner [mm] (As-built length of first sensor)
% L_sensor = 9.53;    % Length from TC junction to corner [mm] (As-built length of first sensor)
L_sensor = 7.65;    % Length from TC junction to corner [mm] (As-built length flosser head sensor)
```

Online Data Platform for NEUP HTGR (in progress)

- Special thanks to Mitchell Plummer’s team.
- Organized by FY and NEUP project number.
- Each entry currently has its resultant scientific publications:
  - Project abstract
  - Final report
  - Journal publications
  - Conference proceedings
- This will be integrated into the ART-GCR official webpage soon.

DOE-ART | NEUP Website | **NEUP Prj Files**

NDMAS

NEUP LIBRARY

Version: 0.15
Status: Checked in and viewable by authorized users.

Name	Title	PI/Authors
Year : 2021 (3)		
21-24104 Technical Abstract	Thermal Hydraulics Investigation of Horizontally Orientated Layout Micro HTGRsunder Normal Operation and PCC Conditions Using Integrated Advanced Measurement Techniques	Muthanna H. Al-Dahhan
21-24111 Technical Abstract	Experimental Investigations of HTGR Fission Product Transport in Separate-effect Test Facilities Under Prototypical Conditions for Depressurization and Water-ingress Accidents	N.K. Anand
21-24287 Technical Abstract	Investigating heat transfer in horizontal micro-HTGRs under normal and PCC conditions	Hitesh Bindra Kansas
Year : 2020 (1)		
20-20074 Technical Abstract	Characterization of Plenum to Plenum Natural Circulation flows in a High Temperature Gas Reactor (HTGR)	Masahiro Kawaji
Year : 2019 (2)		
19-17037 Technical Abstract	Investigation of HTGR Reactor Building Response to a Break in Primary Coolant Boundary	Shripad T. Revankar
19-17183 Technical Abstract	Mixing of helium with air in reactor cavities following a pipe break in HTGRs	Masahiro Kawaji
Year : 2018 (3)		
18-15058 Technical Abstract	High-resolution Experiments for Extended LOFC and Steam Ingress Accidents in HTGRs	Xiaodong Sun
Sun 2020	High-resolution Experiments for Extended LOFC and Steam Ingress Accidents in HTGR	Xiaodong Sun
Wang et al 2021	A hybrid porous model for full reactor core scale CFD investigation of a prismatic HTGR	Chengqi Wang, Yang Liu, Xiaodong Sun, Piyush Sabharwall
Year : 2017 (4)		
17-13115 Final Report	Experimental Determination of Helium/air Mixing in Helium Cooled Reactor	Victor Petrov

Conclusion

- A literature review and research survey have been conducted for the completed and ongoing NEUP-HTGR projects awarded from FY2009 to FY2021.
- Identified examples that NEUP-funded projects have not been well examined while having high importance with low to medium knowledge level:
  - Thermal fluid stratification;
  - Mixing in the upper inlet plenum;
  - RCCS performance and behavior.
- 2022 ANS winter meeting summary submitted.
- Online data platform in development.

Future Work

- ART Milestone Report in September 2022.
- Collaborating with university PIs to gather more detailed information for experimental and computational work.
  - Refining the HTGR phenomena summary chart continuously.
- Finalizing the data platform and keeping it updated with new funded NEUP-HTGR projects.
- Choosing 1-2 projects and performing benchmark studies for code verification and validation (V&V).

Reference

1. U.S. Department of Energy, Nuclear Energy University Program (NEUP). [cited 2022 July]; Available from: https://neup.inl.gov/SitePages/Home.aspx.
2. INL Advanced Reactor Technologies (ART) Program. [cited 2022 July]; Available from: https://art.inl.gov/SitePages/ART%20Program.aspx.
3. Ortensi, J., *Prismatic Coupled Neutronics Thermal Fluids Benchmark of the MHTGR-350 MW Core Design: Benchmark Definition.* Publication, OECD/NEA, Paris, 2012.
4. X-energy's Reactor: Xe-100*.* [cited 2022 July]; Available from: https://x-energy.com/reactors/xe-100.
5. Ball, S.J., et al., *Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs) Volume 2: Accident and Thermal Fluids Analysis PIRTs*. 2008, Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).

Thank you for your attention!

Questions?

ART Advanced Reactor Technologies

GAS-COOLED REACTORS