GAS-COOLED REACTOR

ADVANCED REACTOR TECHNOLOGIES PROGRAM

July 18, 2024

HTGR Validation: NEUP Survey and Database

Data Reporting Standard for HTGR Thermal-Fluid Experiments

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DOE ART GCR Review Meeting

Hybrid Meeting at INL

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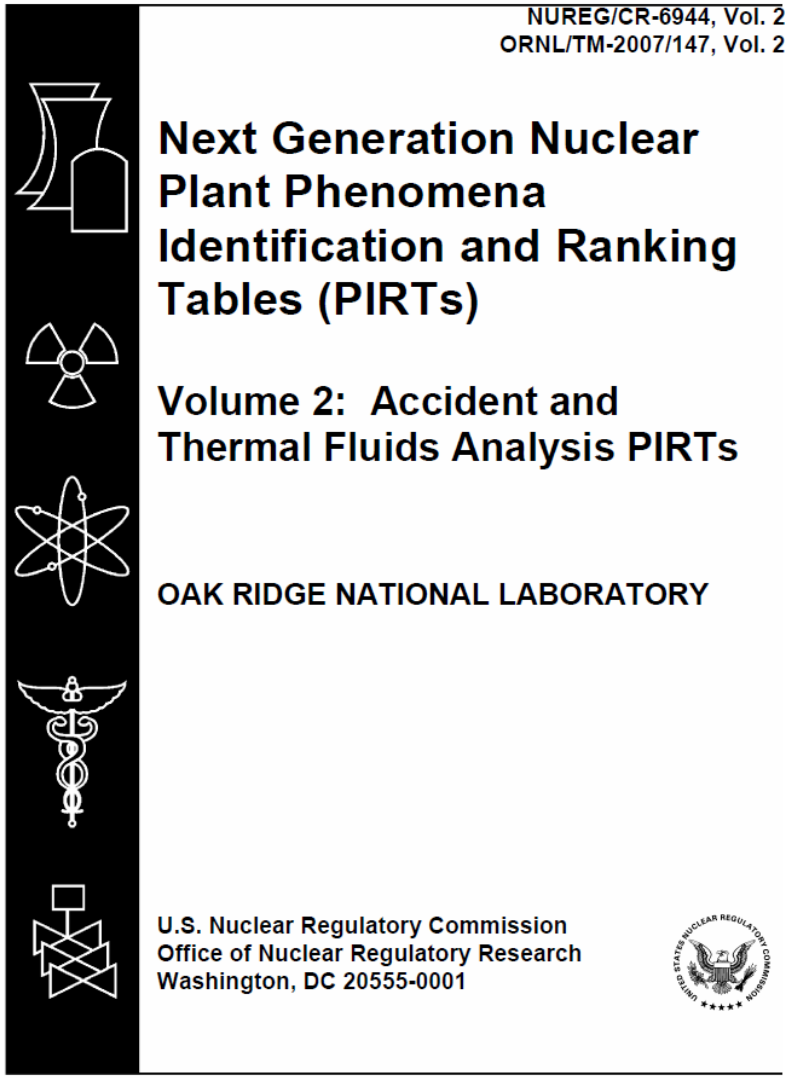
Introduction

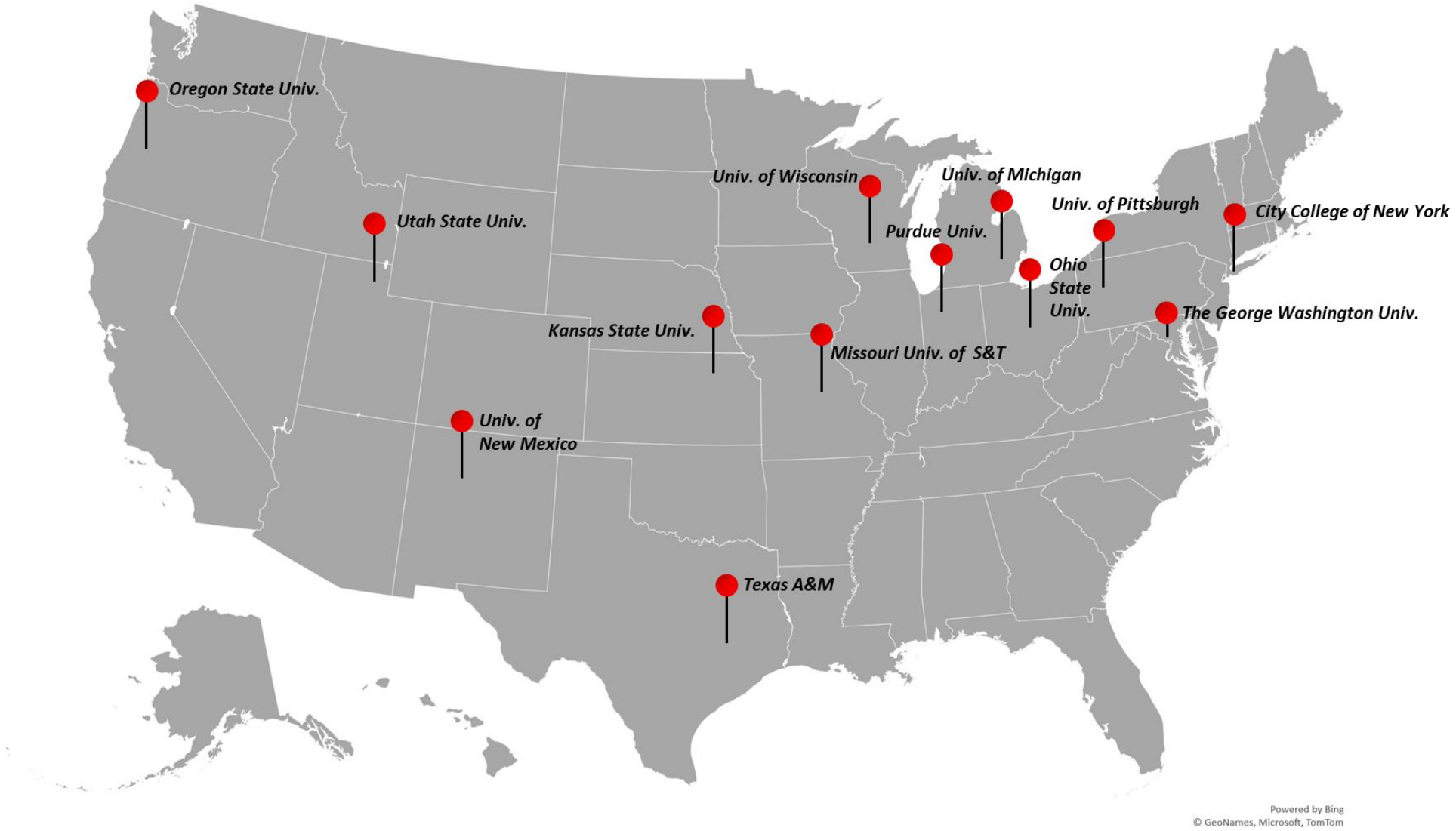
- Since 2009, there are in total 36 DOE NEUP [1] projects focusing on the thermal-fluid phenomena related to High-Temperature Gas-cooled Reactor (HTGR), producing **a large amount of high-quality validation data**, however,
  - Data is distributed at universities and *has not been disseminated to the 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 work 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 have conducted an extensive survey [3] to:
  - **Assess completed and ongoing NEUP-funded HTGR-TH related 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, and
  - **Standardize the data reporting framework** for the experimental and computational data.

Background – HTGR PIRT Study

- In 2008, an accident and thermal-fluids phenomena identification and ranking process was conducted by a panel of experts [4] 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:
  - Loss of flow accident (LOFA, or Pressurized Conduction Cooldown – PCC);
  - Loss of coolant accident (LOCA, or Depressurized Conduction Cooldown – DCC);
  - Air ingress following the DCC;
  - Steam/water ingress, etc.



NEUP-Related HTGR Projects – Universities Participated



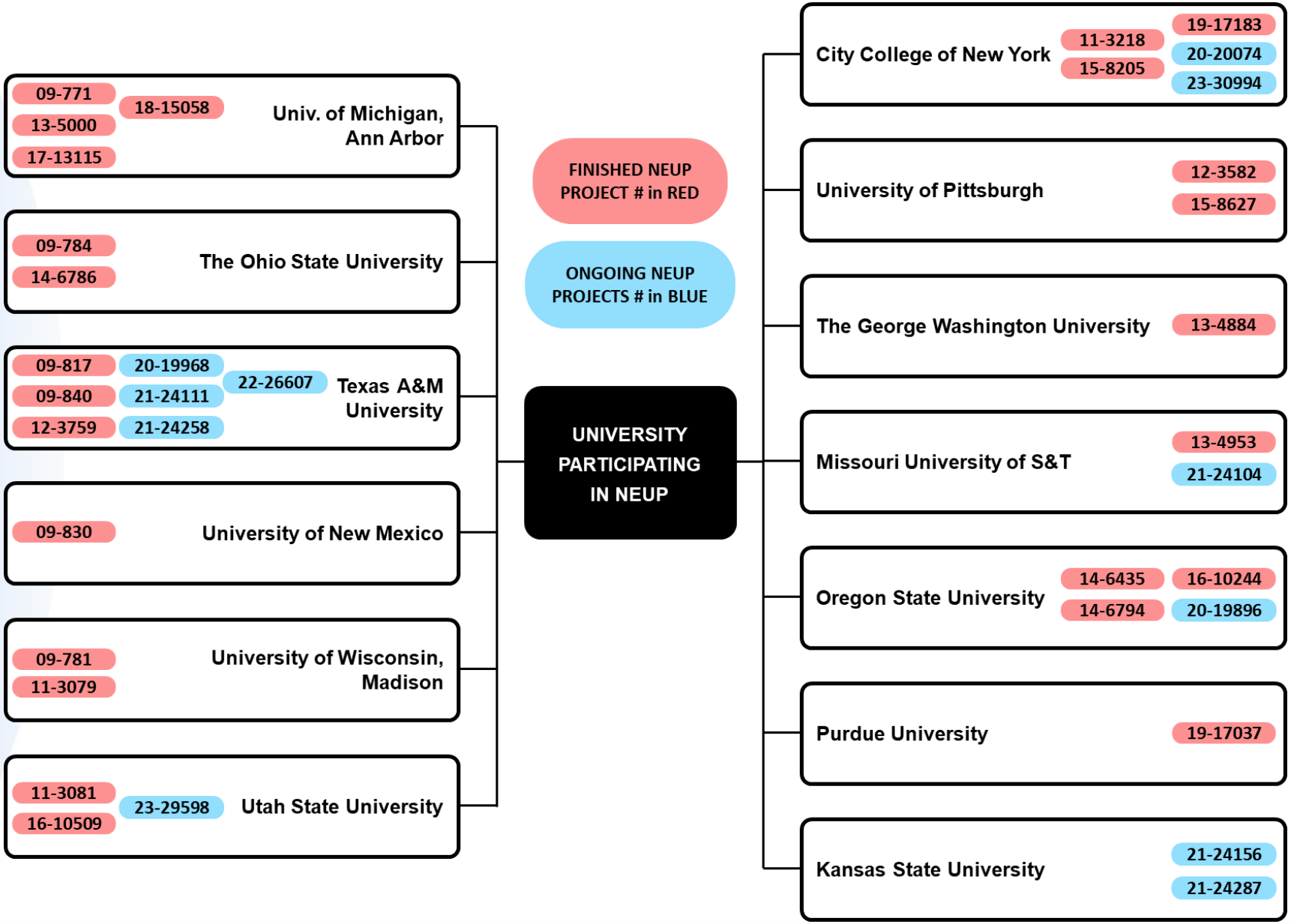
DOE NEUP Project List for HTGR-TH (FY09 – 24)

Project No.	Project Name	Principal Investigator and Affiliation
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	William Martin (University of Michigan)
09-781	Experimental Studies of NGNP Reactor Cavity Cooling System With Water	Michael Corradini (University of Wisconsin)
09-784	Investigation of Countercurrent Helium-air Flows in Air-ingress Accidents for VHTRs	Xiaodong Sun (The Ohio State University)
09-817	CFD Model Development and Validation for High Temperature Gas Cooled Reactor Cavity Cooling System (RCCS) Applications	Yassin Hassan (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	Yassin Hassan (Texas A&M University)
11-3079	Thermal-hydraulic analysis of an experimental reactor cavity cooling system with air	Michael Corradini (University of Wisconsin)
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 Kimber (University of Pittsburgh, now at TAMU)
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	Yassin Hassan (Texas A&M University)
13-4884	Validation data for depressurized and pressurized conduction cooldown, validation data acquisition in HTTF during PCC events	Philippe 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 Klein (Oregon State University)
14-6786	Experimental Investigation and CFD Analysis of Steam Ingress Accidents in HTGRs	Xiaodong Sun (The 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, now at TAMU)

DOE NEUP Project List for HTGR-TH (Cont'd)

Project No.	Project Name	Principal Investigator and Affiliation
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 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)
20-19896	Progression of High Resolution SET and IET Benchmarks on PCC and DCC events in HTGRs	Izabela Gutowska (Oregon State University)
20-19968	Experimental Investigations and Numerical Modeling of Near-wall and Core Bypass Flows in Pebble Bed Reactors	Thien Nguyen, Victor Ugaz, Yassin Hassan (Texas A&M University)
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 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)
21-24156	Experimental Thermofluidic Validation of TCR Fuel Elements Using Distributed Temperature and Flow Sensing	Hitesh Bindra (Purdue University)
21-24258	High-fidelity, Data Science-informed Pebble-bed Reactor Simulation	Jean Ragusa (Texas A&M University)
21-24287	Investigating Heat Transfer in Horizontally Oriented HTGR under normal and PCC conditions	Hitesh Bindra (Purdue University)
22-26607	An Innovative Monitoring Technology for the Reactor Vessel of Micro-HTGR	Lesley Wright (Texas A&M University)
23-29598	Uncertainty Quantification of Model Extrapolation in Neural Network-informed Turbulent Closures for Plenum Mixing in HTGRs	Som Dutta (Utah State University)
23-30994 (IRP)	Exascale Simulation of Thermal-Hydraulics Phenomena in Advanced Reactors and Validation Using High Resolution Experimental Data	Taehun Lee (City College of New York)

List of NEUP HTGR-TH Projects (FY09 – 24)



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
PLENUM MIXING / JET IMPINGEMENT		LOWER PLENUM	12-3582 15-8627	16-10244	16-10244		
		UPPER PLENUM	12-3759	18-15058	18-15058		
		PLENUM TO PLENUM	13-4953 16-10509 23-29598	20-20074	20-20074	23-29598	
INGRESS		AIR INGRESS		15-8205 20-19896	09-784 15-8205 13-4884 17-13115 14-6435 20-19896		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	PRESSURIZED LOSS OF FLOW	DEPRESSURIZED LOSS OF FLOW	LOAD CHANGE (TRANSIENT)	STEAM GENERATOR TUBE BREAK
CONJUGATE HEAT TRANSFER (CORE)	FORCED CONVECTION	09-771, 21-24104, 11-3081, 21-24287, 16-10509	11-3218, 21-24104, 21-24287	11-3218, 21-24156		
	NATURAL CONVECTION	14-6794, 16-10509	14-6794, 15-8205	14-6435, 15-8205, 21-24156		
RCCS PERFORMANCE		09-781, 13-4953, 09-817, 20-19896, 11-3079	20-19896	20-19896	09-781, 11-3079, 09-817, 13-5000	
CORE BYPASS FLOW		09-830, 15-8627, 20-19968	15-8205	09-840, 15-8205		
FLUID STRATIFICATION				14-6435		19-17183
MULTI-PHYSICS (FISSION PRODUCT, SAFETY ANALYSIS, THERMAL-MECHANICAL, ETC.)		20-19896, 21-24258, 22-26607	20-19896	19-17037, 21-24111, 20-19896, 21-24156	22-26607	19-17037

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
PLENUM MIXING / JET IMPINGEMENT		LOWER PLENUM	12-3582, 15-8627	16-10244	16-10244		
		UPPER PLENUM	12-3759	18-15058	18-15058		
		PLENUM TO PLENUM	13-4953, 16-10509, 23-29598	20-20074	20-20074	23-29598	
INGRESS		AIR INGRESS		15-8205, 20-19896	09-784, 15-8205, 13-4884, 17-13115, 14-6435, 20-19896		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, 21-24156		
		NATURAL CONVECTION	14-6794, 16-10509	14-6794, 15-8205	14-6435, 15-8205, 21-24156		
RCCS PERFORMANCE			09-781, 09-817, 11-3079, 13-4953, 20-19896	20-19896	20-19896	09-781, 11-3079, 09-817, 13-5000	
CORE BYPASS FLOW			09-830, 15-8627, 20-19968	15-8205	09-840, 15-8205		
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Development of Data Reporting Standards

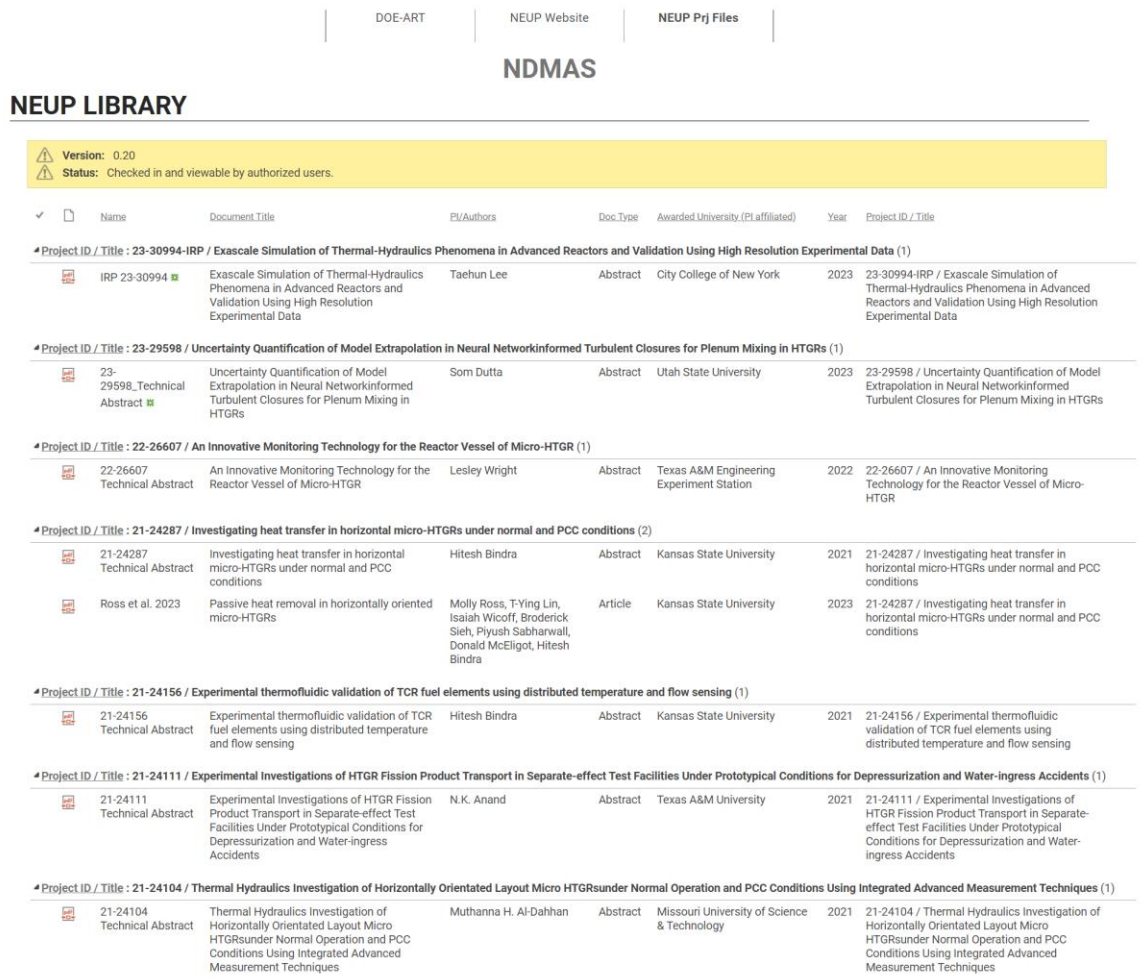
- To harness the full potential of these valuable experimental efforts, it is crucial to establish a standardized framework for the systematic reporting of data derived from the experimental NEUP projects.
- Instead of a conventional readme file, the structured framework proposed in this work ensures a comprehensive and cohesive presentation of HTGR-related TH research, and the metadata can be summarized as follows:
  - Introduction and project scope
  - Experimental setup and facility description
  - Figures of merit (primary measurement variables)
  - Measurement positions and conditions
  - Data collection methodology
  - Computational models (if applicable)
  - Relevant scientific publications

File Sharing and Data Reporting Standards

- The suggested documentation of experimental data should be attached and encompasses the following components:
  - Computer-aided design (CAD) files of the experimental facility:
    - Detailed CAD files illustrating the experimental facility, with additional information pertaining to uncertainties or tolerances.
    - File Types: .prt, .sld, .ass, .drw, etc.
  - Equipment and measurement position
    - Excel/Text file detailing equipment specifications, measurement positions, uncertainties, and measurement frequencies. A supplementary text file provides additional context and details regarding equipment configurations.
    - File Types: Excel file, Text file
  - Experimental data (raw and/or processed)
    - Raw and/or processed experimental data files in formats such as MATLAB (.mat), comma-separated values (.csv), etc. The recorded measurements must be systematically arranged based on the corresponding measurement timestamp, along with the precise spatial coordinates denoting the location for each distinct experimental case. Measurement uncertainties should also be included and discussed.
    - File Types: .mat, .csv, etc.
  - Data processing files
    - Files containing data processing code in formats such as Python (.py), MATLAB (.m), etc. These files are essential for replicating data processing steps and conducting further analysis.
    - File Types: .py, .m, etc.

Online Data Platform for NEUP HTGR-TH Study

- Organized by the fiscal year awarded and NEUP project number.
- Each entry currently has its resultant scientific publications:
  - Project abstract
  - Final report
  - Journal publications
  - Conference proceedings, etc.
- Selected projects to be tested to incorporate experimental data matrices.
- This will be integrated into the ART-GCR official webpage (https://art.inl.gov).



Ongoing V&V Efforts
- Ranking Table Development for Experimental Facilities

- Incorporated the HTGR-related projects:
  - NEUP experimental projects
  - Available experimental facilities, such as ANL NSTF, OSU HTTF, etc.
- Identified investigation topics and phenomena of interest.
- Collected information for data resolution and time scheme.
- Ranking parameters considered as:
  - Raw data availability;
  - Data uncertainties quantification;
  - Scientific publications availability;
  - Computational models accessibility;
  - Integral vs. Separate effect test.
- *To be noticed: The score will involve subjective judgement, and the ranking criteria still in development.*

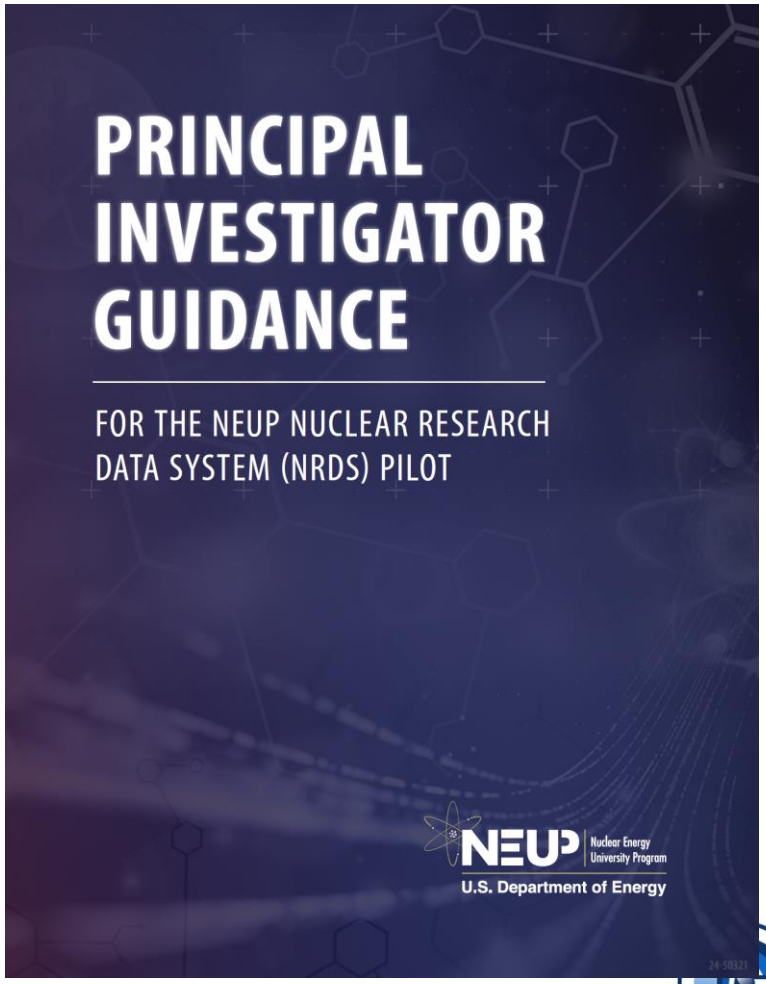
Ranking Table Example for HTGR-related Experimental Facilities

Facility/ NEUP Project	Location	Point of Contact (PI)	Phenomena of Interest / Purpose	Data Resolution (Description)	Time scheme: [SS, Transient]	Topic Type: [TH, Neutronics, Chemical, Multi-physics]	Raw Data (#)	Data Uncertainties (#)	Report/ Publications (#)	Computational Models (#)	Integral? (#)	Score
NEUP 17-13115	Univ. of Michigan	Victor Petrov	He/Air mixing behavior during the HTGR DLOFC and Air Ingress accidents for small and medium sized breaks.	Jet velocity data (PIV and LDV), mass flow rate, temperature, pressure	Transient	TH	80	70	60	70	70	**350**
NEUP 11-3081	Utah State University	Barton Smith	PIV vs CFD data validation for a heated flat plate	Heat flux, Velocity field (PIV)	SS	TH	80	70	50	60	80	**340**
NEUP 18-15058	Univ. of Michigan	Xiaodong Sun	High-resolution data on jet interaction at HTGR upper plenum; Moisture absorption of heated graphite.	Velocity field (PIV and LDV)	SS, Transient	TH, Chemical	70	70	60	70	70	**340**
NEUP 15-8627	Univ. of Pittsburgh	Mark Kimber	Flow interaction between core bypass and coolant jet flows	Velocity Field (PIV), Reynolds Stress, Turbulent kinetic energy, vorticity	SS	TH	70	70	70	60	70	**340**
NEUP 13-5000	Univ. of Michigan	Annalisa Manera	RCCS at upper plenum and turbulent jet mixing	Velocity field (PIV and LDV)	SS	TH	80	70	50	60	70	**330**
NEUP 15-8205	CCNY	Masahiro Kawaji	Forced convection and bypass flow phenomena, natural circulation flow and heat transfer	Velocity (hot-wire measurement), temperature (IR camera, and k-type TC)	Transient	TH	80	70	60	60	50	**320**
NEUP 09-781	UW, Madison	Michael Corradini	Water RCCS performance	Temperature and mass flow rate (time resolved)	SS, Transient	TH	70	60	70	60	50	**310**
NEUP 16-10509	Utah State University	Barton Smith	Buoyancy driven/opposed flow measurements	Velocity field (PIV), temperature (TC), pressure, mass flow rate	SS, Transient	TH	70	70	50	50	70	**310**

(to be continued)……

NEUP Nuclear Research Data System (NRDS) Pilot

- NEUP Management Team initiated the NRDS pilot program in April 2024 with DOE Nuclear Science User Facilities (NSUF) funding support.
- Working groups have been developing data guidelines for NEUP projects and establishing a clear process for the release of data through NRDS, a data repository co-located with INL's High Performance Computing (HPC) infrastructure.
- Three phases have been planned and started accordingly:
  - Identify project and metadata for direct input into the NRDS pilot system
  - Provide guidelines for preparing raw or processed data and associated documents
  - Expanding and engaging more NEUP teams into NRDS Database (https://nrds.inl.gov)



Conclusion

- Updated the matrix for Thermal-Fluid Phenomena and Accident Scenario with the completed and new awarded projects.
- Developed the data reporting standards for HTGR-TH related research.
- Collaborating with INL research team through NRDS Pilot and LDRD project
  - Collecting and organizing online data platform over INL HPC
  - Ranking table of code V&V for experimental facilities

FY25 Work

- Communicating with university PIs to gather more detailed information for experimental and computational work.
  - Refining the HTGR phenomena summary chart continuously
  - Identify the research gaps
- Finalizing the data platform and keeping it updated with new funded NEUP-HTGR TH-related projects.
- Utilizing the developed ranking table for HTGR-TH research facilities, choosing the top 1-2 projects and performing benchmark studies.

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Thank you!

Questions?

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U.S. DEPARTMENT OF ENERGY

Reference

1. U.S. Department of Energy, Nuclear Energy University Program (NEUP). [cited 2023 July]; Available from: https://neup.inl.gov/SitePages/Home.aspx.
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4. 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).

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