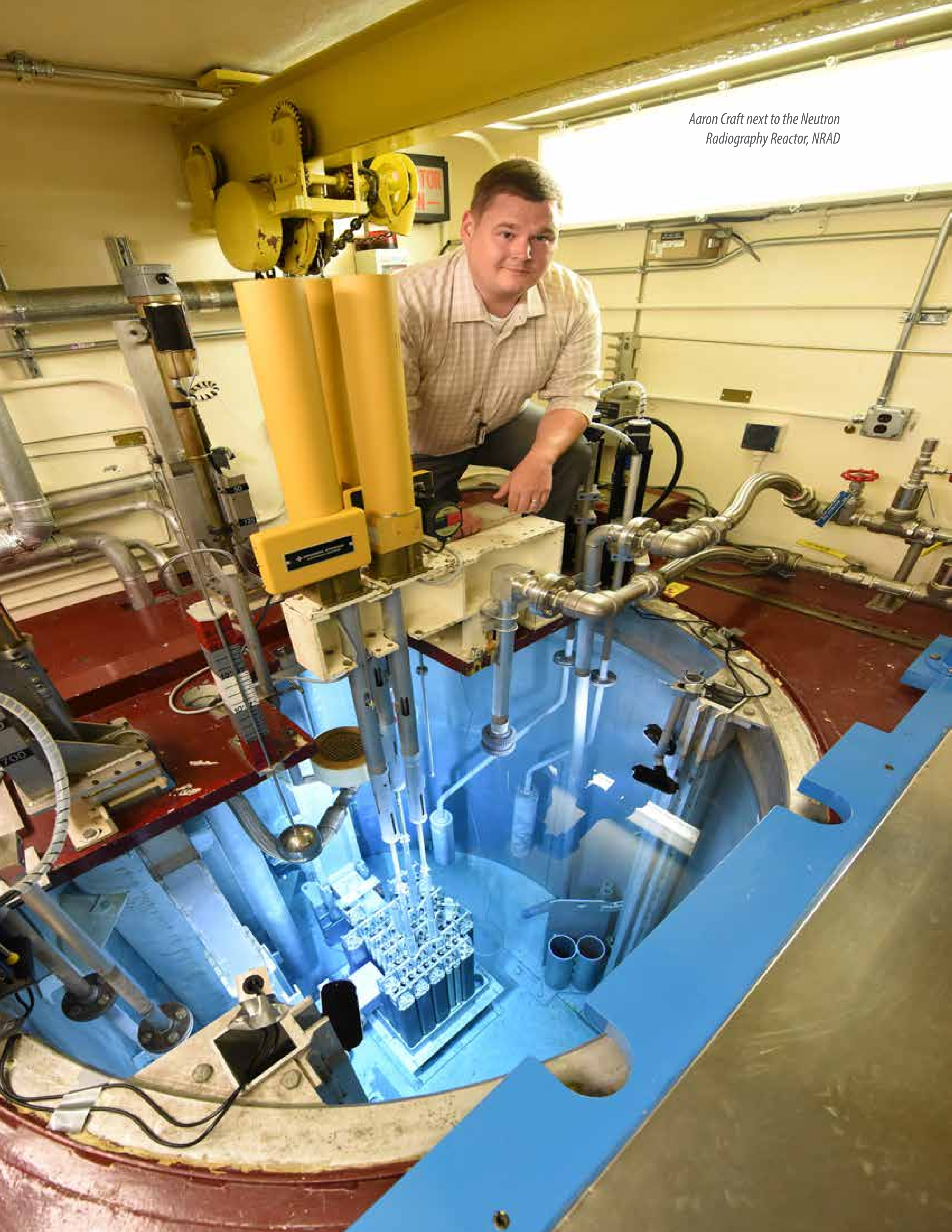
12TH WORLD CONFERENCE ON NEUTRON RADIOGRAPHY

WCNR 12

2 - 7 JUNE 2024 | IDAHO FALLS, USA

Idaho National Laboratory



Aaron Craft next to the Neutron Radiography Reactor, NRAD

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SCIENTIFIC BOARD

LOCAL ORGANIZATION COMMITTEE

Aaron Craft | Chairman
Hassina Bilheux | Co-Chairwoman
Tandy Bales | Co-Organizer
Lisa Wells | Co-Organizer

SCIENTIFIC ADVISORY BOARD

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Thomas Bücherl | Germany
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Javier Santisteban | Argentina
Burkhard Schillinger | Germany
Takenao Shinohara | Japan
Markus Strobl | Switzerland
Alessandro Tengattini | France
Anton Tremsin | USA
Pavel Trtik | Switzerland

Prismatic Springs,
Yellowstone National Park, Wyoming

WCNR-12 CONFERENCE SCHEDULE

SUNDAY, 02 JULY 2024

Walking Discussion

7:00	Depart from Hilton Garden Hotel to Yellowstone National Park
11:00	Lunch
12:00	**Walking Discussion** (Old Faithful)
13:00	Depart Old Faithful
16:55	Arrive back at Hotel

17:00 Pre-Registration / Exhibitor Setup

18:00	**ISNR Board Meeting**

19:00 Welcome Reception (Hilton Garden Inn Conference Center)

MONDAY, 03 JUNE 2024

Pre-session

7:00	Registration & Poster Setup (Session A)
8:00	Welcome & Announcements

Opening Session

8:10	Opening Speaker – **Joseph Bevitt** | Neutron Tomography and the Virtual World of Paleontology
8:35	**Aaron Craft** | Digital Neutron Imaging of Irradiated Nuclear Fuels at Idaho National Laboratory

Facility Overviews | Chair: Burkhard Schillinger

9:00	**Ulf Garbe** | 10 Years of User Operation on DINGO at OPAL
9:25	**Markus Strobl** | Advances in Neutron Imaging Techniques and Applications at PSI
9:50	**Michael Schulz** | Recent Advances in Neutron Imaging at FRM II
10:15	Break

NDT & Standards | Chair: Aaron Craft

10:45	**Hassan Malik** | Optimization of Gadolinium Contrast Enhancement for Improved Neutron Radiography of Ceramic Core Materials in Jet Engine Turbine Blades
11:05	**Ranggi Ramadhan** | Strain Mapping Using Bragg Edge Imaging: Preliminary Round-Robin Campaign
11:25	**Martin Wissink** | Commercial Neutron Imaging with An Accelerator-Based Neutron Source
11:45	**Joshua Vanderstelt** | An Overview of Current and Future ASTM Neutron Imaging Standards
12:05	Poster Pitches - Session A
12:30	Day 1: Working Lunch: Non-Destructive Testing Discussion led by Aaron Craft
14:00	Poster Session A
16:00	Break

Advanced Techniques | Chair: Anton Tremsin

16:30	**Krystyna Lopez |** Searching for Exotic Polarized Neutron-Polarized Electron Interactions Using Neutron Imaging
16:50	**Burkhard Schillinger |** A Vertical Neutron Beam Device Used To Examine Liquids
17:10	**Adrian Losko |** Advancements in Imaging Detectors Based on Event Mode Data Acquisition
17:30	**Su Ann Chong |** Neutron-Sensitive Microchannel Plates with Quad Timepix3 Readout (MCP/TPX3) Detector for Time-Of-Flight Neutron Imaging
17:50	**Alexander M. Long |** Unlocking the Potential of Event-Based Neutron Imaging Systems for Energy Resolved Neutron Imaging at LANSCE
18:10	Adjourn
18:15	**ASTM E07.05 Meeting**

TUESDAY, 04 JUNE 2024

Pre-session

7:00	**Poster Setup (Session B)**
8:00	Welcome & Announcements

Material Science | Chair: Pavel Trtik

8:10	**Shieren Sumarli** | Neutron Radiography Techniques for Operando Studies During Laser Powder Bed Fusion
8:30	**Axel Griesche** | Crystallographic Phase Transformations and Corresponding Temperature Distributions During GTAW of Supermartensitic Stainless Steel Visualized by Neutron Bragg Edge Imaging
8:50	**Leslie G. Butler** | Friction Stir Additive Manufacturing: Neutron Interferometry and Bragg Edge Imaging
9:10	**Winfried Kockelmann** Presenting for **Saurabh Kabra** | Stroboscopic Bragg Edge Radiography of Twin Formation in a Magnetic Shape Memory Alloy
9:30	**Anton Tremsin** | Optimization of Liquid-Solid Interface and the Translation Speed for Crystal Growth Through Energy-Resolved Neutron Imaging
9:50	Break

Engineering | Chair: Hassina Bilheux

10:20	**Thawatchart Chulapakorn** | Deformation Structures in Steel Revealed by Neutron Imaging
10:40	**Daisuke Ito** | Measurement of Boiling Two-Phase Flow Pattern Dynamics Using High-Speed Neutron Imaging
11:00	**Takenao Shinohara** | Pulsed Neutron Imaging Study of Energy-Related Devices for Automotive Vehicles
11:20	**Pavel Trtik** | Simultaneous Measurements of Surface Phenomena, Diffusivity and Solubility of Liquids Exposed to High Gas Pressures
11:40	**Frederik Ossler** | Neutron Imaging To Study the Interaction Between Hydrogenous Substances and Porous Carbon Materials and Hydrogen Release in Biomass Pyrolysis
12:00	Poster Pitches - Session B
12:30	**Group Photo**
12:40	Day 2: Working Lunch: Material Science Application Discussion led by Hassina Bilheux
14:00	**Poster Session B**
16:00	Break

Facility Upgrades | Chair: Jean Bilheux

16:30	**Alessandro Tengattini |** NeXT 2.0, the Neutron and X-Ray Tomograph at ILL
16:50	**Yuxuan Zhang |** Grating Interferometry Imaging at the High Flux Isotope Reactor
17:10	**Robert Nshimirimana |** Optimization of Neutron Collimator and Shielding for the Refurbishment of the Neutron Imaging Facility at Necsa

Software and Machine Learning | Chair: Jean Bilheux

17:30	**Qianru Zhan |** Enhancing Neutron Tomography for Corrosion Analysis: A Machine Learning Approach for Noise Reduction and Detail Enhancement
17:50	**Mohammad Samin Nur Chowdhury |** Subspace Extraction Algorithm for High-Quality Reconstructions in Hyperspectral Neutron Computed Tomography
18:10	**Shimin Tang |** HyperCT: An Artificial Intelligence Adaptive Hyperspectral Neutron Computing Tomography System
18:10	Adjourn
18:15	**Presentations for WCNR-13 & Board Elections**

WEDNESDAY, 05 JUNE 2024

Pre-session

8:00	Welcome & Announcements

Energy & Environment | Chair: Daniel Hussey

8:10	**Maha Yusuf** | In-Situ, Non-Destructive, 3D Neutron Imaging of Lithium Plating Following Extreme Fast-Charging of Full-Cell Lithium-Ion Batteries
8:30	**Anders Kaestner** | Tomographic Study of Rhizobox Dynamics
8:50	**Cedric Qvistgaard** | White Beam Polarized Neutron Imaging of Weak Ion Currents in Energy Devices Via Induced Magnetic Fields
9:10	**Yuto Obayashi** Presenting for **Hideki Murakawa** | Visualization of Liquid Water Behavior in a Polymer Electrolyte Fuel Cell Under High-Temperature Operation Using a Neutron Radiography
9:30	Break

New Facilities | Chair: Takenao Shinohara

10:00	**Jana Matouskova** | TRIXIE -- Development and Construction of a New Neutron Imaging Instrument in The Czech Republic
10:20	**Andreas Meyer** | A New Thermal Neutron Imaging Instrument at the Institut Laue Langevin
10:40	**Afaf Ouardi** | Final Design of Neutron Imaging System "NERA" at the Maamora Reactor
11:00	**Naoya Odaira** | Experiments and Numerical Simulations on Fast Neutron Imaging
11:20	**Frederico A. Genezini** | Neutron Radiography at the Energy and Nuclear Research Institute/Brazil - IPEN: the Story So Far and Future Perspectives
11:40	**Manuel Morgano** | ODIN @ESS: Commissioning of the Instrument
12:00	**Hassina Bilheux** | Commissioning the VENUS Imaging Beamline at the Spallation Neutron Source
12:20	Day 3: Working Lunch: Cultural Heritage Discussion led by Aaron Craft

VENUS Plenary | Chair: Hassina Bilheux

14:00	**Aaron Hanks** | The Construction of the VENUS Imaging Instrument at the Spallation Neutron Source: the Engineering Perspective
14:30	**Jean Bilheux** | Data Workflow and Software Tools at VENUS
15:00	**Anton Tremsin** | Overview of Science Capabilities of VENUS Beamline
15:30	**Adrian Bruegger** | The Future CUPI^{2}D Beamline at the STS: A General Update Including Optics Design
16:00	Break

Nuclear Engineering | Chair: Winfried Kockelmann

16:30	**Sarah Weick** | In-Situ Neutron Radiography with Hydrogenated Tensile Samples in the INCHAMEL Facility
16:50	**Aaron Colldeweih** | Post Ramp and LOCA Simulation Characterization of Cr-Coated Zircaloy-4
17:10	**David Chichester** | The Fuel Motion Monitoring System at TREAT - Current Status and Future Plans
17:30	**Markus Strobl** Presenting for **Florencia Malamud** | Spatially Resolved Texture Characterization of Cold-Rolled Zircaloy-4 Cladding by Bragg Edge Imaging
17:50	**Youngju Kim** | Observation of Nano-Void Coalescence in Hydrogen-Fatigued Vessel Steel Using Neutron Dark Field Imaging
18:10	**Sven Vogel** | Pulsed Neutron Characterization of Irradiated Fuels at Lansce
18:10	Adjourn

THURSDAY, 06 JUNE 2024

Pre-session

8:00	Welcome & Announcements

Cultural Heritage | Chair: Ulf Garbe

8:10	**Eberhard Lehmann** | How To Perform Cultural Heritage Research by Using Neutron Imaging?
8:30	**Tushar Roy** | Characterization of Ancient Indian Archaeological Artefacts Using Neutron Imaging
8:50	**Ocson Cocen** | Insights From Neutron and X-Ray Computed Tomography Analysis on Archaeological Nails From Bois De Châtel, Avenches, Switzerland
9:10	**Joseph Bevitt** | The Invisible Revealed: Cultural Forensics with Neutrons at the Powerhouse Museum
9:30	Break

Detectors | Chair: Yasushi Saito

9:45	**William Chuirazzi** | Boron-Based Neutron Scintillator Screen Characterization with X-Rays and Neutrons
10:05	**Bernhard Walfort** | Scintillation Screens for Neutron Imaging
10:25	**Jarek Glodo** | Low-Cost Scintillator Composites for Thermal Neutron Imaging
10:45	Break

Neutron Grating Interferometry / Dark Field Imaging | Chair: Markus Strobl

11:00	**Camilla Buhl Larsen** | Orientation-Dependent Grain Level 3D Strain Evolution in Oligocrystalline CoNiGa
11:20	**Simon Sebold** | Shape and Size Distribution of the Magnetic Domain Structure in Electrical Steel Measured with Neutron Grating Interferometry
11:40	**Alex Backs** | Observation of the Macroscopic Magnetic Domains in Silicon Steel During Magnetization with Polarized Neutron Imaging
12:00	**Alaleh Aminzadeh** | Neutron Diffusive Dark-Field Imaging Using a Structured Mask
12:20	Day 4: Working Lunch: Neutron Grating Interferometry Discussion led by Hassina Bilheux **2nd Board Meeting with New Board Members (Exec. Conf. Room)**

Neutron Optics | Chair: Alessandro Tengattini

14:00	**Manoraj Dhanalakshmi Veeraraj** | Development of An Achromatic Neutron Lens
14:20	**Yasushi Saito** | Enhancement of Spatial Resolution in High-Speed Neutron Imaging Using a Multi-Slit Collimator
14:40	**Daniel Hussey** | Development Plans for the NIST Cold Neutron Imaging Instrument

Conclusions & Outlook

15:30	**Break**
16:00	**Travel To Conference Dinner**
17:00	**Conference Dinner at EBR-1**
19:30	**Travel To Hotel**

Materials and Fuels Complex (MFC)

FRIDAY, 07 JUNE 2024

INL Facilities Tour

7:30	Travel To MFC
8:20	Process Through Security / Walk To Tour Location
8:40	**Rotating Tour (TREAT / HFEF / IMCL)**
9:40	Walk To Next Tour Location
10:00	**Rotating Tour (TREAT / HFEF / IMCL)**
11:00	Walk To Next Tour Location
11:20	**Rotating Tour (TREAT / HFEF / IMCL)**
12:20	Walk To Lunch Location
12:40	Day 5: Working Lunch: Post-Irradiation Examination at MFC by Colin Judge
13:40	Travel To Idaho Falls

INL TOUR INFORMATION

The Idaho National Laboratory (INL) facilities tour is scheduled for **Friday, June 7, 2024.**

For those attending, board the bus at **07:30 a.m.** outside the Hilton Garden Inn. The Materials and Fuels Complex (MFC) facilities to be toured include the Transient Reactor Test (TREAT) Facility, Hot Fuel Examination Facility (HFEF), and Irradiated Materials Characterization Laboratory (IMCL). Lunch will be provided at MFC. We will return to the Hilton Garden Inn at approximately 1:40 p.m.

What to Wear

Appropriate clothing should include long pants and shirts with sleeves as well as closed-toe and closed-heel shoes (covering the entire foot). No shorts, tank tops, sleeveless tops, dresses, skirts, capri pants, high heels, or sandals are permitted.

Sturdy shoes with closed-toe and closed-heel are required. Natural fiber slacks (cotton) are preferable due to the sensitivity of INL personal contamination monitors and their ability to read naturally occurring radon, which is attracted to synthetic fiber (i.e., polyester).

Guidelines

Visitors are not allowed to carry prohibited articles on INL property. These include:

- Alcohol or illegal drugs
- Firearms, ammunition, or explosive devices
- Cameras, recording devices, or portable transmitting devices
- Personal radiation monitoring devices (Radiation monitoring is conducted by trained and certified INL personnel using instrumentation that is calibrated by accredited laboratories. If a visitor would like to know more about monitoring, please ask your escort.)
- Cellular phones are allowed on the INL, but may not be taken into facilities.

The Transient Reactor Test (TREAT) Facility allows researchers to test nuclear fuels and materials in off-normal and accident conditions, providing key data that helps improve safety and efficiency.

Transient Reactor Test Facility

Irradiation

The Transient Reactor Test (TREAT) Facility at Idaho National Laboratory is a national asset that is helping to re-establish the United States' leadership in an essential nuclear research field. It will foster the development of new ways to provide baseload and load following electrical power. Transient testing is an essential component of the United States and international efforts to develop robust, safer nuclear fuels, and to bring innovative reactor technologies to the market.

Transient testing involves the application of controlled, short-term bursts of intense neutron flux directed toward a test specimen in order to study fuel and material performance under off-normal operational conditions and hypothetical accident scenarios. After the transient test, the fuel or material is analyzed at a post-irradiation examination (PIE) facility. The results of these examinations are then evaluated and used in advancing fuel or material design and qualification.

TREAT is a highly capable test reactor. Detailed real-time monitoring of the specimens during a test is possible via the hodoscope, a system that detects fast neutron signatures from experiments, and other experiment and core instrumentation. This instrumentation, coupled with PIE, allows scientists to determine the appropriate safety limits for the fuels and materials in nuclear power reactors. TREAT's simple, self-limiting, air-cooled design can safely accommodate multipin test assemblies, enabling the study of fuel melting, metal-liquid reactions, overheated fuel and coolant reactions, and transient behavior of fuels for high temperature system applications.

The TREAT facility operated from 1959 through 1994, when it was placed in standby mode. A resurgence of interest in developing innovative nuclear technologies has restored the demand for transient testing. TREAT was restored in 2018 and is currently supporting experiment programs.

TREAT provides transient testing of nuclear fuels and materials. The facility is used to study fuel melting behavior, interactions between fuel and coolant, and the potential for propagation of failure to adjacent fuel pins under conditions ranging from mild upsets to severe accidents.

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TREAT was restarted in 2018 after being placed on standby in 1994.

TREAT is an air-cooled, thermal-spectrum test facility specifically designed to evaluate the response of reactor fuels and structural materials to accident conditions. The reactor was originally constructed to test fast-reactor fuels, but its flexible design has also enabled its use for testing of light-water-reactor fuels as well as other exotic special-purpose fuels, such as space reactors. TREAT has an open-core design that allows for ease of experiment instrumentation and real-time imaging of fuel motion during irradiation, which also makes TREAT an ideal platform for understanding the irradiation response of materials and fuels on a fundamental level.

TREAT was placed on standby in 1994. TREAT was restarted in 2018 and is currently supporting experiment programs. TREAT provides a valuable capability to support efforts to develop accident-tolerant fuels for light-water reactors as well as the advanced reactor fuels, both of which will allow nuclear power to remain the primary source of emission-free baseload energy in the future.

BASIC CAPABILITIES:

- High-intensity (20 GW), short-duration (<100 ms) neutron pulses for severe accident testing
- Shaped transients at intermediate powers and times (flexible power shapes up to several minutes duration)
- 120 kW steady state operation
- Testing capability for static capsules, sodium loops and water loops
- Neutron-radiography facility

KEY INSTRUMENTS:

- Nondestructive examination of assemblies up to 15 feet long in steady state operating mode by neutron radiography
- Neutron 'hodoscope,' providing real-time imaging of fuel motion during testing
- Open core design suitable to instrument experiments during testing

FOR MORE INFORMATION

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National Laboratory

21-50083_TREAT_R1 (Updated: 2021)

Hot Fuel Examination Facility

Post-irradiation Examination of Fuels and Materials

The Hot Fuel Examination Facility is the largest hot cell dedicated to radioactive material research at Idaho National Laboratory.

The Hot Fuel Examination Facility (HFEF) is Idaho National Laboratory's flagship facility for conducting post-irradiation examinations of fuels and materials. HFEF, located at the Materials and Fuels Complex, is a national research asset with the largest inert atmosphere hot cell dedicated to nuclear materials research in the U.S.

HFEF provides the ability to remotely handle and perform detailed nondestructive and destructive examination of highly irradiated fuel and material samples. Its argon-atmosphere hot cell, labs and special equipment handle a variety of fuel forms, including tiny particles, four-foot research reactor plates and full-sized commercial rods. HFEF supports INL's mission of research and development of safer and more efficient fuel designs.

KEY CAPABILITIES:

- HFEF has two large, shielded hot cells. The main cell, which is 70 by 30 feet, is stainless steel-lined. It's fitted with two 5-ton cranes and 15 workstations, each with a 4-foot-thick window of oil-filled glass and a pair of remote manipulators. The second hot cell is an air cell used to decontaminate materials and equipment.
- Laser puncture and gas collection with the gas assay sample and recharge (GASR) from fuel samples helps researchers gain needed information on fission gas and helium release.
- Precision gamma scanning (PGS) allows scientists to precisely determine the location of radioactive elements in fuel and material samples.
- The fuel accident condition simulator (FACS) furnace enables fuel and material sample testing under worst-case scenarios involving temperatures of up to 2,000 C for extended periods. This allows scientists to understand performance and improve the safety of fuel designs.
- The Neutron Radiography Reactor is a 250 kW steady state Training Research Isotopes General Atomics (TRIGA) reactor co-located within and adjacent to HFEF. It is equipped with two separate radiography stations for neutron radiography of fuel and materials.
- Fuel refabrication for testing in the Transient Reactor Test (TREAT) facility.

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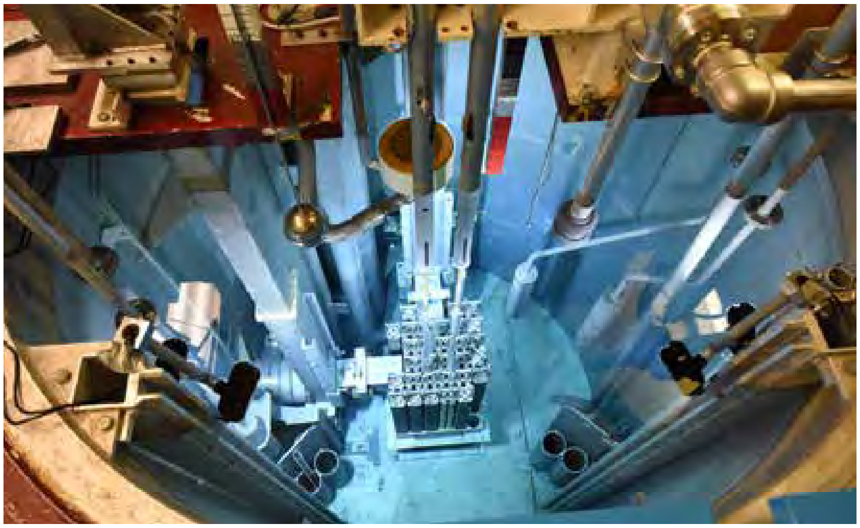

The NRAD reactor provides a neutron source for indirect-film and digital radiography of irradiated fuels and materials, neutron computed tomography and neutron diffraction

The Hot Fuel Examination Facility (HFEF) is a multi-program hot cell facility. There are two adjacent shielded hot cells (the main cell and decontamination cell), a shielded metallography box, an unshielded hot repair area, and a waste-characterization area. HFEF provides shielding and containment for remote examination, processing, and handling of highly radioactive and TRU-bearing materials in its argon-atmosphere hot cells, unshielded labs, support areas and special equipment for handling, examining, and testing of highly radioactive materials.

BASIC CAPABILITIES:

- Nondestructive and destructive post-irradiation examination of irradiated samples in two large, heavily shielded hot cells.
  - » Machining and disassembly of fuel and material experiments
  - » Neutron film and digital radiography
  - » Neutron tomography
  - » Neutron diffraction
  - » Visual examination and dimensional examination
  - » Gamma scanning/ gamma tomography
  - » Fission-gas-release measurement
  - » Sample preparation for metallography, chemical and isotopic analysis, and optical microscopy
- Mechanical testing of irradiated fuels and materials
- Bench-scale electrochemical separations research.
- Precision milling, welding, and machining.
- Handling and loading facilities capable of receiving large shipping casks and fuel assemblies up to 13 feet long.
- Furnaces for simulating accident conditions at temperatures up to 2,000 C for extended periods.

KEY INSTRUMENTS:

Nondestructive instruments include:

- NRAD reactor
- Autoradiography
- Visual examination machine
- Eddy current probe for measurement of oxide thickness
- Precision gross and isotopic gamma spectrometer
- Element contact profilometer bow & length machine (fuel rods)
- Profilometry and eddy current measurement bench (fuel plates)
- Pycnometer

Destructive instruments include:

- Laser puncture gas collection and analysis system
- Fuel accident condition simulator (FACS) furnace
- Metal waste form furnace
- Remote load frame

FOR MORE INFORMATION

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Irradiated Materials Characterization Laboratory

Advanced Post-Irradiation Examination

The Irradiated Materials Characterization Laboratory is home to a variety of high-end instruments that allow researchers to study irradiated fuels and materials at the micro, nano and atomic levels, which is where irradiation damage occurs.

The Irradiated Materials Characterization Laboratory (IMCL) is a unique, 12,000-square-foot facility located at Idaho National Laboratory's Materials and Fuels Complex. The hazard category 2 facility incorporates many features designed to allow researchers to prepare and conduct microstructural-level investigations on irradiated fuel safely and efficiently.

IMCL focuses on microstructural, microchemical, and micromechanical analysis and thermophysical characterization of irradiated nuclear fuels and materials. IMCL's unique design incorporates advanced characterization instruments that are sensitive to vibration, temperature, and electromagnetic interference into modular radiological shielding and confinement systems. The shielded instruments allow characterization of highly radioactive fuels and materials at the micro, nano, and atomic levels, the scale at which irradiation damage processes occur.

Enabled by its modular design, IMCL will continue to evolve and improve capability throughout its 40-year design life to meet the national and international user demand for high-end characterization instruments for the study of nuclear fuel and materials.

Combined with INL's advanced computer modeling techniques, this understanding will enable advanced fuel designs, and reduce the time needed for fuel development and licensing.

BASIC CAPABILITIES:

- Preparation of high-activity samples
- Optical microscopy
- Electron probe microanalysis (EPMA)
- Dual-beam focused ion beam (FIB)
- Transmission electron microscopy (TEM)
- Local electrode atom probe (LEAP)
- Scanning electron microscopy (SEM)
- Measurement of material physical and thermal properties
- X-ray microscopy (XRM)
- X-ray diffractometer (XRD)

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KEY CAPABILITIES/INSTRUMENTS:

Application	Instrument	Capabilities	Configuration
Sample Preparation	SSPA - Shielded sample preparation area	Optical microscope, polishing and grinding, sample cutting in hot cell, glovebox, and hood	Shielded
Advanced Microscopy, Microchemistry, Micromechanical Testing	SEM - JEOL 7600	High-resolution scanning electron microscope (SEM) equipped with electron back-scatter diffraction, energy dispersive X-ray spectroscopy (EDS) and wavelength dispersive spectroscopy (WDS) detectors	Benchtop
	EPMA - Shielded Cameca SX100R	Quantitative compositional analysis of solid specimens on a micrometer spatial scale. Detectors and electronics are shielded to 3 Ci of 137 Cs to allow for trace element detection. Measures elements from B to Cm.	Shielded
	STEM - FEI Titan Scanning Transmission Electron Microscope	Equipped with probe corrector, super-X EDS, electron energy loss spectroscopy (EELS), DENSolutions D6 heating holder (1573 K), tomography holders, vacuum transfer holder, Hysitron PI-95 PicoIndenter	Benchtop
	APT - LEAP 5000 Atom Probe	3D imaging and chemical analysis at sub-nanometer scale	Benchtop
	FIB - FEI Quanta 3D FEG Focus Ion Beam	Preparation of minute samples for TEM, APT, and micromechanical testing	Shielded
	FIB - Thermo G3 Plasma Focus Ion Beam	Preparation of block samples for rapid 3D reconstruction, micromechanical testing, and microscale thermal property testing	Shielded
	FIB - Thermo G4 Helios Hydra Plasma Focus Ion Beam with TOF-SIMS	Equipped with secondary ion mass spectrometer (SIMS), EDS, and electron backscatter diffraction (EBSD) for sample preparation, imaging, microstructural, and chemical analysis	Benchtop
Thermophysical property measurement	LFA - Netzsch LFA 427 laser flash analyzer	Thermal diffusivity, contact resistance from room temperature to 2000 C, specific heat, thermal conductivity (under development)	Shielded
	TGA/MS - Simultaneous TGA/DSC+MS Netzsch STA 409C Skimmer	Measure specific heat, phase transformation temperatures and enthalpies, fission off-gas composition, mass change from room temperature to 2000 C	Shielded
	TCM - Thermal conductivity microscope	Spatial resolved thermal diffusivity, thermal conductivity with a spatial resolution of 50 µm from room temperature to 300 C	Shielded
	PPMS - Quantum Design Physical Property Measurement System	Electrical, thermal, thermodynamic and magnetic property measurement at temperatures from 1.8 K to 400 K and magnetic field range 0-9 T	Benchtop
Structure analysis and tomography	XRD - PANalytical powder X-ray diffractometer	Bulk X-ray diffraction with heating stage	Benchtop
	XRM - ZEISS Xradia 520 Versa X-ray microscope	Nondestructive 3D imaging of materials over 4 orders of magnitude in length scales (0.1-100 cm)	Benchtop
Mechanical testing	Mini-tensile tester	Tensile testing with digital image correlation (DIC)	Shielded

FOR MORE INFORMATION

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National Laboratory

Experimental Breeder Reactor-I (EBR-I)

WCNR 12

PRESENTATION ABSTRACTS
MONDAY, 3 JUNE 2024

MONDAY, 03 JUNE 2024

Pre-session

7:00	**Registration & Poster Setup (Session A)**
8:00	Welcome & Announcements

Opening Session

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18:10	Adjourn
18:15	**ASTM E07.05 Meeting**

Neutron Tomography and the Virtual World of Paleontology

Joseph J. Bevitt

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In paleontology, X-ray radiography and tomography (CT) are critical tools employed in the characterisation of fossil forms through the structural evaluation of bone surface features. Where further details are required, nondestructive CT complements physical thin-sectioning to investigate the internal structure of fossils. In this manner, specimens can be evaluated as juvenile, sub-adult or adult, while the presence of medullary bone infers that the animal was gravid, and therefore female. Details such as these are essential in differentiating ontogenetic (age related) and sexual from phylogenetic differences, resulting in improved taxonomic definitions and revealing temporal changes in morphology.

Museums have traditionally either been ignorant of, or hesitant to employ neutron tomography (NT) in paleontology. This is due primarily to warnings of residual induced radioactivity, the unclear benefit over X-ray CT, and limited accessibility to neutrons. Unlike in most other fields, legal ownership, ethics, import-export declarations, chain-of-custody requirements, insurance and object loan agreements and suitable storage all complicate efforts to conduct paleontological science at major facilities.

Over the last 10-15 years, museums have increasingly engaged with neutron facilities, first through exploratory studies on low-value specimens, before rapidly transitioning to challenging (X-ray opaque) and high-impact specimens.

This talk draws from the extraordinary outcomes of the diverse merit-based user community to summarise the benefits of neutrons over X-rays and trace the development of a world-leading program of paleontology research using the DINGO neutron imaging instrument at the Australian Nuclear Science and Technology Organisation (ANSTO) [1].

Highlights include the first evidence that crocodiles ate dinosaurs [2], the world's oldest-known fossil heart [3], neurosensory diversity in early reptiles [4] and discovery of new dinosaur and pterosaur species. These and other examples will further demonstrate the challenges and lessons learned, the evolving technical and ethical demands of the paleontological community.

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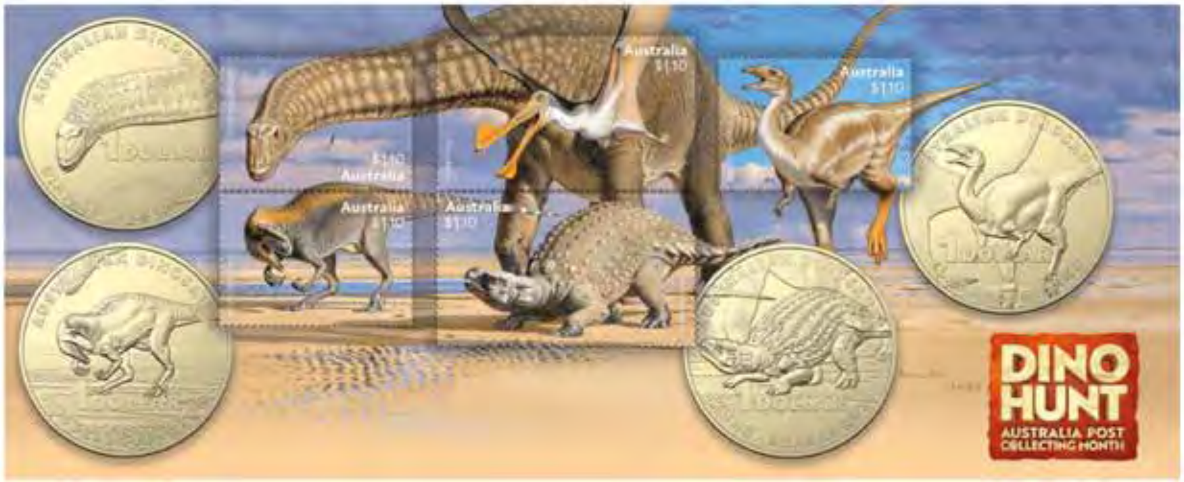
A small, complete, Early Permian skull with articulated mandibles‘; from the fossiliferous karst deposits near Richards Spur, Oklahoma. Ref: Gee, Bevitt, & Reisz, *A juvenile specimen of the trematopid Acheloma, Frontiers in Earth Science*, 7 (38), 2019.

New prehistoric crocodilian discovered with a dinosaur in its stomach. Ref [2].



Neutrons and synchrotron X-rays go public. ANSTO-assisted dinosaur and pterosaur discoveries featured on Australian coins and stamps in 2022.

Digital Neutron Imaging of Irradiated Nuclear Fuels at Idaho National Laboratory

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Neutron radiography provides more information about the internal structure of irradiated nuclear fuels than any other nondestructive testing technique to date. The immense gamma-ray dose rates emitted by highly radioactive irradiated nuclear fuels has traditionally necessitated the use of transfer method neutron radiography methods in which a latent radiographic image in the form of an activation pattern of a foil is transferred to an imaging medium such as film or image plates. Transfer method techniques have remained the state of the art for examination of highly radioactive irradiated nuclear fuels for the nearly seven decades that this field has existed. This paper describes efforts over the preceding decade to advance the state of the art from transfer methods to established modern techniques and novel concepts, with a long-term goal of enabling neutron computed tomography of highly radioactive irradiated nuclear fuels as a routing post-irradiation examination technique.

Initial efforts established transfer method computed radiography using standard X-ray photostimulable storage phosphor image plates as an alternative to using film. Direct transfer method was pursued in which a transfer foil coated with phosphor material was activated and subsequently transferred out of the neutron beam where the image was read by a digital camera. This method was able to capture a digital image of irradiated nuclear fuels with only 5 minutes exposure, fast enough to enable neutron tomography, but the spatial resolution was unacceptable. Modern microchannel plate detectors were able to directly examine highly-irradiated nuclear fuel, but the field of view was insufficient. Modern digital camera-scintillator systems could also examine irradiated fuels, but the intense gamma-ray field emitted from the sample diminished the signal-to-noise ratio, which limited its applicability to lesser irradiated fuels emitting lower dose rates. Scintillator screen development efforts pursued screens that used ^{10}B rather than ^{6}Li as a neutron converter in an effort to improve the neutron-to-gamma signal to noise ratio, and these efforts are ongoing.

Current efforts include establishing an upgraded digital camera-scintillator type system for direct digital radiography and computed tomography of transient-irradiated nuclear fuels. Additionally, an event mode imaging system is being evaluated for its applicability to highly-radioactive samples, which is promising because of its ability to separate single gamma-ray and neutron capture events.

Few facilities in the world can routinely examine highly irradiated nuclear fuels using neutron beam techniques. This paper provides an overview of Idaho National Laboratory's neutron-based examination capabilities at two of its nuclear research reactors, along with previous and current efforts towards advancing the state of the art and establishing digital neutron computed tomography as a routine post irradiated examination technique.

10 Years of User Operation on DINGO at OPAL

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The neutron imaging instrument DINGO received its operational license in October 2014 to support research at ANSTO. DINGO provides a useful tool to give a different insight into objects because of different contrast compared to X-rays and high sensitivity to light elements. Since starting hot commissioning with first friendly users the research community is constantly growing with a strong boost from the World Conference for Neutron Radiography (WCNR-11) in 2018. In the field of industrial application, it has shown promising results for studying cracking and defects in concrete or other structural material. A major part of applications from both sides of the community, research and industrial user, was demanding the high-resolution setup and fast scans on DINGO. In the original design DINGO could provide a minimum pixel size of 27 µm with 2k x 2k pixel. Upgrades of the past ten years involved a neutron microscope setting to achieve 1.7 µm pixel size. In addition, we upgraded to new cameras moving from CCD to scientific CMOS and finally using astronomy CMOS cameras with 26 or 60 mega pixel chips. A new graphical user interface was developed for these astronomy cameras. These new cameras are demanding on computing and data storage as well. We developed a custom-made CT reconstruction package to streamline the data reduction process and offer a variety of rendering software like VGStudio, AVIZO and Dragonfly. Next to all technical upgrades, we like to present a collection of scientific and commercial high lights over the last ten years. These highlights cover a large variety of scientific field like materials science, engineering science, palaeontology, cultural heritage and many more.

Finally, I give an outlook on further planned upgrades on drill core imaging, fast imaging and data analysis to keep DINGO competitive for another ten years of great science. Further new developments in the area of neutron ghost imaging and high-pressure neutron imaging are close to completion and will be available early 2025.

Advances in Neutron Imaging Techniques and Applications at PSI

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Energy research and additive manufacturing have remained and become very prominent topics in neutron imaging, respectively, and have triggered a number of remarkable instrumental and methodical developments in recent years. Similar holds true for hard and soft condensed matter research and many other applications in our field tackling societal challenges. This contribution intends to provide an overview of the developments of neutron imaging methods and closely entangled their applications at PSI in recent years. In order to provide a flavor of such developments three prominent examples shall be mentioned here.

Metal additive manufacturing plays an outstanding role in the current evolution of industrial production. In support of a rapid development towards reliable 3D printing and the exploration of its full potential neutron imaging at PSI has contributed with various observations and investigations targeting e.g. strains, texture and density variations forming during the production process [1,2]. In particular, the Applied Materials Group at PSI provides a downsized metal printing machine (nSLM) for operando and in-situ investigations utilizing different imaging techniques such as for example polarized neutron imaging for the observation of magnetic phase transitions in steels during additive manufacturing.

The environmental impact of all instances of our life and of our technologies are in the focus of evaluation of carbon footprints for every action taken. In this framework nano crystalline cellulose and its structural design and growth through ice templating have been put forward for its remarkable isolation properties, which the material can exhibit in the context of construction and housing but also for other technological applications. With multi-directional dark-field contrast imaging [3] we have developed a unique tool to map the fibre orientation in the bulk of such materials and to shine light on the correlation of humidity and thermal conductivity.

Finally, in the remit of energy research to support the endeavor for a green energy future numerous neutron imaging studies are conducted since many years to provide details on the inner working of electrochemical processes in fuel cells, electrolysers and batteries. In this context we have supported various seminal studies involving not only the operando mapping of lithiation phases through different advanced neutron imaging approaches, but lately, in particular, also observations targeting the impact of the degradation of electrolyte triggered e.g. through temperature variations during battery cycling [4,5]. To this end we map the features of the inelastic neutron cross section, similar to earlier approaches to map aggregate state and temperature distribution of water in fuel cells at low temperatures or, to close the cycle, the temperature gradient and evolution in metal samples during selective laser melting additive manufacturing.

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Recent Advances in Neutron Imaging at FRM II

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The neutron imaging group at FRM II, Garching operates the two-neutron imaging facilities ANTARES and NECTAR. ANTARES provides a cold neutron spectrum, which gives high sensitivity for even small changes of composition in a sample and is used for neutron imaging with high spatial resolution as well as advanced techniques such as imaging with polarized neutrons or neutron grating interferometry (nGI). The instrument NECTAR is a unique facility that provides a fast fission neutron spectrum that allows the investigation of even very bulky samples and shows contrast complementary to X-rays or gammas. Additionally, thermal neutrons and gamma radiography are also available at NECTAR in a multi-modal approach.

While FRM II has not been running due to repair works for an extended period of time, we have performed many upgrades to our instruments such as the new X-ray setup at ANTARES or a new rail system and sample stage at NECTAR. Additionally, we have performed many experiments at other facilities to support ongoing internal and user projects such as the development of event-mode neutron imaging detectors, studying the defect evolution in additively manufactured samples, investigating the process of freeze drying with neutron imaging or using neutron grating interferometry to track the magnetic domain behavior in electric steel under tensile stress

In our contribution, we will give an overview of recent achievements and activities of the neutron imaging group at FRM II and show the new experimental possibilities users will have at our instruments.

Optimization Of Gadolinium Contrast Enhancement for Improved Neutron Radiography of Ceramic Core Materials in Jet Engine Turbine Blades

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Neutron Radiography plays a pivotal role in the non-destructive testing of critical components, such as jet engine turbine blades. These turbine blades are cast from specialized nickel alloys, using ceramic cores to form internal cooling passages. Leftover ceramic core inside the cooling passages of these blades can be detected through Neutron Radiography. However, the core must be contrast enhanced by bonding a strong neutron absorber to it, for example gadolinium. Currently, a solution composed of gadolinium nitrate hexahydrate in water and methanol with 3.5% gadolinium by weight is used, with the castings held under the solution for 10 minutes. In this study, we investigate the impact of varying the gadolinium concentration and the hold time in the solution on the visibility of ceramic cores in neutron radiographs. Our objective is to assess if modifying these parameters enhances the contrast and visibility of the ceramic core. Enhancing the contrast could make new applications possible in addition to improving the detection of ceramic core in cast turbine blades.

Strain Mapping using Bragg Edge Imaging: Preliminary Round-Robin Campaign

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In recent years, strain mapping using Bragg edge neutron analysis has found its way into engineering research. For the technique to mature into an established tool for academic and industrial research, it is required to have some type of good practice guide or standard. Looking at the example of neutron diffraction, this can be initiated by a cross-facility benchmarking round-robin exercise with a common set of samples. The aim of such an activity is to benchmark the known and new capabilities on different types of instruments, and to assess levels of accuracy, precision, and detection limits of Bragg edge transmission imaging mainly for, but not limited to, strain mapping. We have performed measurements on a common set of samples, including a AlSiC metal matrix composite (MMC) (Fig 1a), on several neutron imaging and diffraction instruments. The purpose of the current campaign is to (i) characterize sample/ sample types for a Bragg edge strain mapping round-robin, (ii) demonstrate the importance of a round-robin activity, and (iii) gauge the interest of the facility and communities in joining the effort. Through measurement of various sample types, we gained insights into the suitability of each for the round-robin, and thus for designing a dedicated Bragg edge round robin sample set. From the measurement campaign at multiple imaging beamlines, we can see the effect of instrument parameters on the Bragg edge shape (Fig. 1b) and investigate how it affects the strain maps. By including neutron diffraction instruments, we can dissect the through-thickness averaged strains produced by Bragg edge imaging (Fig 1c & 1d). This is an important insight regarding the interpretation of Bragg edge strain mapping results.

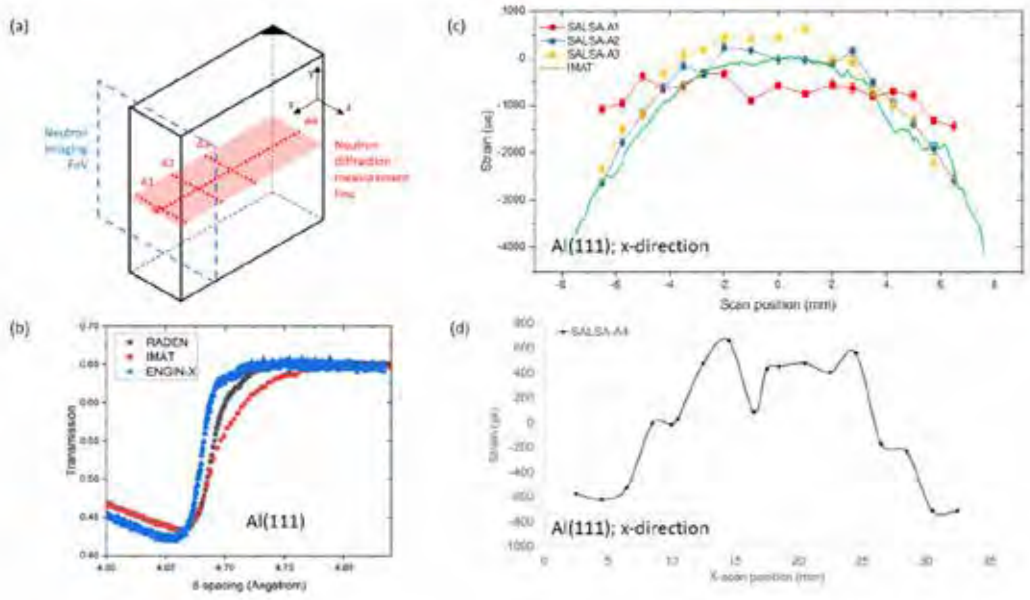

Fig 1. (a) Illustration of AlSiC MMC sample, showing positions of imaging and diffraction measurements; (b) Al(111) Bragg edges measured at 3 instruments; (c) Comparison of strains measured by imaging (IMAT) and diffraction (SALSA) and (d) strain profile through sample thickness. All strains calculated using different d_0.

Commercial Neutron Imaging with an Accelerator-Based Neutron Source

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Neutron imaging is a powerful and complimentary tool to other nondestructive testing (NDT) methods due to the high penetration of neutrons through dense, high atomic number materials and high contrast to certain low atomic number elements such as hydrogen. The primary NDT applications for neutron radiography are the detection of residual core material in single-crystal turbine blades and the inspection of mission-critical aerospace pyrotechnic devices. Historically, production-scale commercial neutron radiography has only been available at a handful of nuclear research reactors, which face challenges with limited availability, low scalability, high regulatory burden, and service interruptions due to both planned maintenance and upgrades or unplanned outages due to fuel element issues. To address these challenges, Phoenix has designed and deployed an accelerator-based neutron source built from the ground up for the express purpose of neutron radiography. The Phoenix neutron imaging center, operating from our facility in Fitchburg, Wisconsin, has been in commercial operation since 2020 and has served dozens of customers across aerospace, defense, and academia, imaging several hundred thousand components per year. This presentation will provide an overview of the facility, examples of typical NDT applications, case studies for industrial neutron computed tomography, and opportunities for researchers to access thermal and fast neutron beams with high uptime, high availability, and short turnaround time. The development of this highly parallel and inherently scalable approach to neutron imaging has demonstrated that a privately funded neutron source is commercially viable, and that we can democratize access to neutrons and potentially significantly increase the user base by bringing neutron production to the open market.

An Overview of Current and Future ASTM Neutron Imaging Standards

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Neutron imaging plays a crucial role in various industrial applications. Adherence to standardized practices is essential for allowing its routine use in any high reliability application. Historical standards were developed based on film-based imaging, and the lack of standard coverage for digital neutron imaging hinders its use within industry. This work reviews the standards currently published by ASTM, as well as those under development, with an emphasis on digital neutron imaging. The expansion of historical standards to allow digital methods as well as the development of new digital imaging-based standards are intended to support an eventual transition to digital neutron imaging within industry and may facilitate expanded use of the method in the future.

Searching for Exotic Polarized Neutron-Polarized Electron Interactions Using Neutron Imaging

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Rare-earth iron garnets are ferrimagnets, with a net magnetization despite the anti-aligned magnetic moments of the rare-earth metal and iron. There is a critical temperature T_c, where the net magnetization should be zero. Because the fractional contribution of the spin and orbital magnetization from the two magnetic species are different, however, there is still a non-zero electron polarization at T_c. We present work performed at the HFIR CG-1D “MARS” neutron imaging beamline, where the first images of a compensated ferrimagnet with spatial resolution have been observed above, at, and below T_c using neutron polarimetry. This technique has allowed us to characterize the distribution and homogeneity of magnetic domains throughout a sample of terbium iron garnet (Tb_3Fe5O_{12}). We will discuss these results and future plans to improve these measurements using upgraded magnetometry, thermometry, magnetic shielding, and temperature control techniques in Summer 2024 at MARS.

A Vertical Neutron Beam Device Used to Examine Liquids

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Neutron beam lines are mostly horizonal, with some exceptions at specialized reactors as the McClellan reactor (Sacramento, USA) that is built underground and has inclined beams, or the small reactor at Kingston college, Canada. These inclined beam lines have never been used to examine thin liquids with at least a vertical beam component.

We have built and tested a new device with one or two crystal reflections on pyrolytic graphite to deflect a horizontal neutron beam to the vertical and examined thin liquids. Initial tests were performed at the TRIGA reactor of Atominstitut Vienna. The initial flux was rather low with about 1E5 n/cm²s, with the deflected flux roughly estimated at two orders of magnitude lower.

Still, it was possible to measure a Gadolinium test target and make out two oil drops floating on about 1 mm of water visible.

Until the time of the conference, we hope to have more measurements on a stronger and cold beamline.

Possible applications are in horizontal diffusion of liquids without the influence of gravity as in vertical setups, or horizontal two-phase flow if done at a more powerful neutron source.

Advancements in Imaging Detectors Based on Event Mode Data Acquisition

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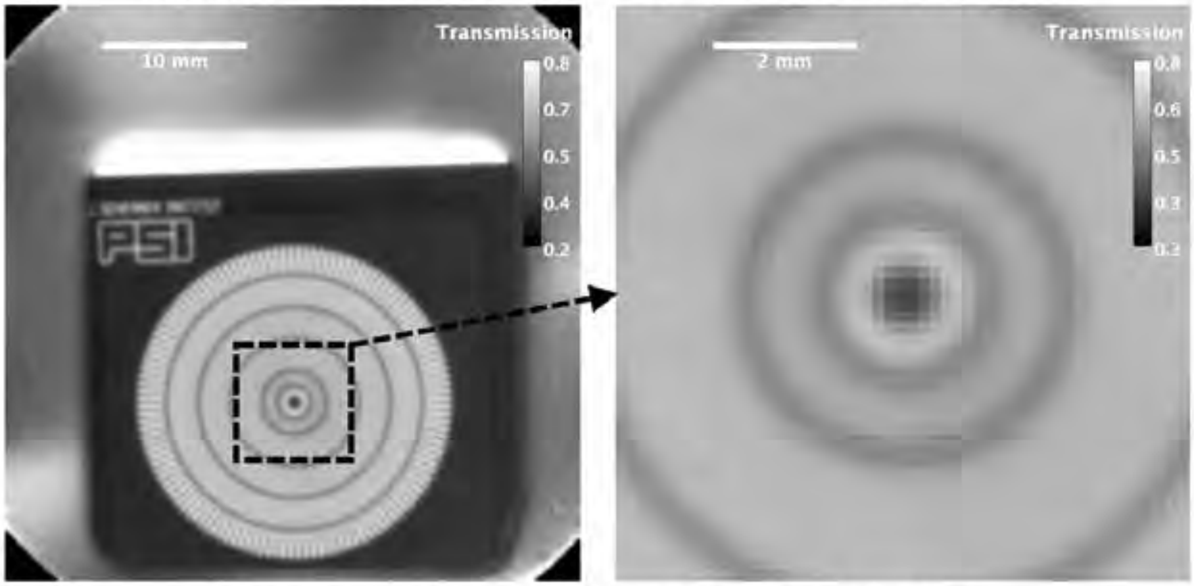
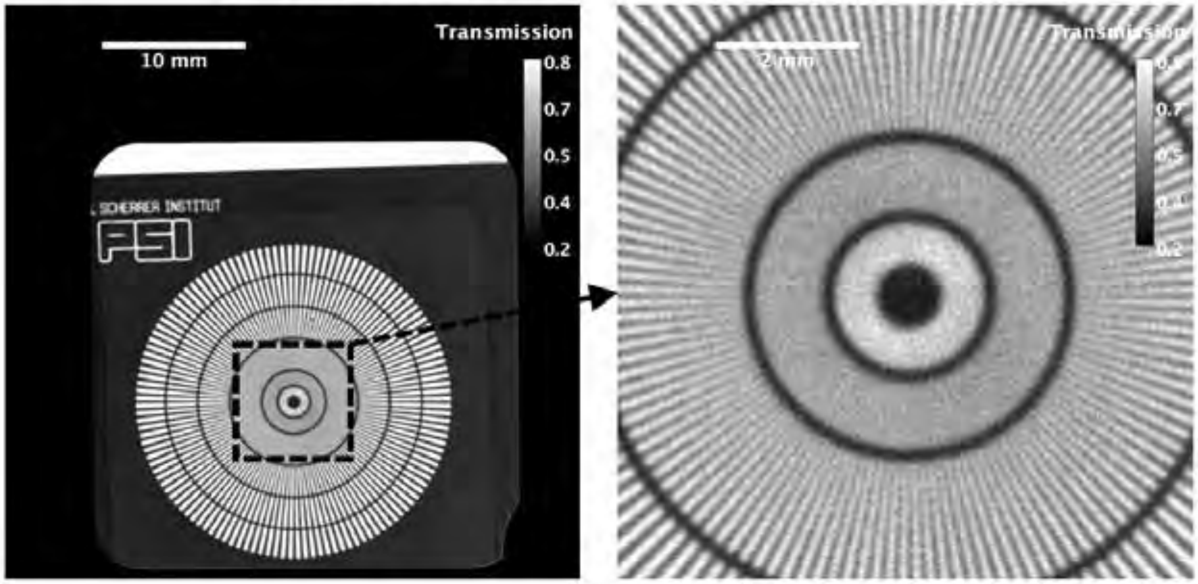
Recently developed event-driven detectors capable of resolving spots of light induced by particle interactions in scintillators opened up new perspectives for detector systems with a concept that fuses the benefits of integrating camera type with counting type detectors [1]. A major drawback for many existing detectors is the tradeoff between temporal and spatial resolution. As such, frame-based camera type detectors with sub millimeter spatial resolution often provide comparatively low temporal resolution in the millisecond range with typically high readout noise, e.g. CMOS or CCD cameras. On the other hand, counting type detectors with sub microsecond temporal resolution and low readout noise, such as PMT or SMT type detectors, often come with pixel sizes in the mm range or larger.

Fundamental to fuse these two types of detectors is the capability of reading individual pixels of imaging sensors with high temporal resolution, such as is the case for the timepix3 sensor. This is achieved via sparse readout, eliminating the need of processing empty image data. Utilizing a light sensitive timepix3 sensor in combination with an image intensifier, the detection of individual neutron interactions led to a significant increase in spatial and temporal resolution beyond the classical limits of regular neutron imaging [1] via reconstruction of the center-of-mass of individual particle interactions (see figure).



Photon event mode at native detector resolution



Neutron event mode at super resolution

Based on this capability, new detectors emerged that allow for time-of-flight imaging using an adjustable field-of-view, ad-hoc binning and re-binning of data based on the requirements of the experiment, including the possibility of particle discrimination via the analysis of the event shape in space and time. It is considered that this novel concept will replace regular cameras in imaging detectors for many applications as it provides superior detection capabilities compared to conventional camera systems, shaping the future of a new generation of detection systems.

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Neutron-Sensitive Microchannel Plates with Quad Timepix3 Readout (MCP/TPX3) Detector for Time-Of-Flight (ToF) Neutron Imaging

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Neutron-sensitive microchannel plates (MCPs) with quad Timepix3 readout (MCP/TPX3) have emerged as a promising neutron imaging camera for neutron imaging with time-of-flight (ToF) capability. The detector consists of a pair of chevron-stacked MCPs coupled to quad Timepix3 readout in a vacuum enclosure kept below $1\text{x}10^{-6}$ Torr. To make the detector neutron sensitive, one of the MCPs is doped with neutron absorbers with very high neutron capture cross-section such as ^{10}B and ^{nat}Gd. The Timepix3 readout is a triggerless event-by-event data driven and zero-suppressed readout. Each Timepix3 chip has 256 x 256 pixels, and each pixel size is 55 x 55 μm^2. It can record the time-of-arrival (ToA) and time-over-threshold (ToT) information of every hit in a pixel simultaneously, up to 80Mhits/s per chip. The timestamping of each hit enables the detector to do ToF imaging, which offers significant advantages over traditional neutron transmission imaging. The ToF capability allows the detector to perform more advanced neutron imaging techniques such as Bragg edge imaging and resonance imaging. In this work, we present a neutron imaging camera capable of ToF imaging with a sub-75 µm spatial resolution using efficient rule-based clustering and peak fitting algorithms to sustain high event rates. The detector demonstrated a rate capability of ≤ 120Mhits/s, a neutron efficiency of ≥ 30% at 4.2 Å, sub-µs time resolution for thermal and cold neutrons, a gamma sensitivity of ≤ 10^{-2} and an active area of 28.2 x 28.2 mm^2.

Unlocking the Potential of Event-Based Neutron Imaging Systems for Energy Resolved Neutron Imaging at LANSCE

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Neutron imaging systems, particularly those employing ultra-fast, event-based light-detection mechanisms, such as the TPX3Cam, have emerged a promising tool for material characterization via pulsed neutrons at the Los Alamos Neutron Science Center (LANSCE). These systems, coupled with neutron-sensitive scintillators and various optical configurations, offer highly customizable setups that are adaptable to a diverse set of neutron-based material characterization techniques. Over the past two years, several materials science flight paths at LANSCE have implemented a wide range of TPX3Cam-based neutron imaging setups, ranging from imaging, to diffraction, and even reflectometry, thus highlighting the robust applications of TPX3Cam-based systems.

More specifically, these TPX3Cam-based neutron imaging systems have been utilized for energy-resolved neutron imaging (ERNI) applications on Flight Path 5 (FP5) at LANSCE, where recent studies on FP5 have demonstrated the efficacy of these systems in imaging both neutron absorption resonances and Bragg edges within several materials using various scintillators. In this presentation, we delve into the methodologies employed and the outcomes of the campaign of measurements performed at LANSCE over the past 2023 run cycle, along with lessons learned and potential best-practices found in using these systems. With a focus on practical applications, we highlight the implications of utilizing TPX3Cam setups along with results in various material characterization techniques, and their impact in advancing neutron imaging in various fields, including materials science, nuclear engineering, and beyond.

WCNR 12

POSTER ABSTRACTS
MONDAY, 3 JUNE 2024

Portable Dual-Mode Imaging System

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Safeguarding against the spread of nuclear weapons and diminishing the risks of nuclear and radiological terrorism globally lies at the heart of the mission undertaken by the DOE/NNSA's Office of Defense Nuclear Nonproliferation (DNN). In line with the NNSA's mission objectives, RMD is actively engaged in the development of a portable, high-resolution radiography detector that integrates both Xray and neutron capabilities. This innovative detector, based on a novel large area scintillator coupled to a commercial flat panel readout, aims to offer exceptional sensitivity for capturing fast neutrons and highenergy X-rays, coupled with rapid frame rates conducive to data analysis essential for materials identification.

We have developed four variations of scintillators for the detector, which include: 1) Embedded ZnS converters, 2) Layered converters, 3) Tin-loaded Organic Glass Scintillators, and 4) Pixelated Organic Glass Scintillators. Through experimentation, we have utilized these scintillator designs to showcase X-ray radiographs with spatial resolutions of less than 70 μm, fast neutron radiographs with spatial resolutions below 250 μm, and high-contrast fast neutron radiographs within a timeframe of less than 10 minutes. Moreover, we have demonstrated scalability for larger imaging areas and enhanced detection efficiencies. The scintillators are engineered in a manner that facilitates their integration into commercially available, large-area a-Si:H flat panels, sCMOS/CCD cameras, and other readouts such as those built using SiPM arrays, thereby forming a portable detector. Depending on the chosen scintillator, the detector can be customized for imaging with X-rays ranging from 400 kVp to 7 MeV, and neutrons spanning from 2.5 MeV (DD) to 14 MeV (DT). In this poster, we will unveil the outcomes of our fast neutron and X-ray imaging data, obtained through the utilization of our detector equipped with a range of innovative scintillators engineered at RMD.

From left: (1) Layered converter - Photograph of a 100 mm^2, 350 μm thick CsI:Tl on 1.6 mm polypropylene (2) 3 cm thick tungsten line-pair phantom (3) Image with 7.5 MeV X-ray, 10 min integration, SD 160 cm (4) Image with 45 min integration, 14.1 MeV DT generator, SD 75 cm, Fluence 3×10^8 n/sec.

This work was supported in part by the U.S. Department of Energy Contract DE-SC0020942.

Understanding Water Management in Electrochemical Devices Using Neutron Imaging

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Efficient water management is crucial in electrochemical devices such as fuel cells, electrolyzers, and reversible fuel cells, as it plays a pivotal role in reducing costs and enhancing overall performance. A comprehensive understanding of in-operando water transport is essential for addressing current limitations and advancing the development of next-generation components for these devices. Neutron imaging is an invaluable technique for visualizing water content within the various components of these devices. Neutrons possess the unique ability to attenuate hydrogen and water while easily penetrating metals. Consequently, neutron imaging allows for the non-invasive examination of water within fuel cells and electrolyzers using standard hardware. Previous research has successfully employed neutron imaging to investigate various aspects of water management in electrode components, and the monitoring of changes in water management resulting from component degradation.

This study focuses on water management within water electrolyzers and unitized reversible fuel cells, with a specific emphasis on investigating the characteristics of porous transport layers (PTLs) and their influence on water transport within these devices. The morphology of PTLs plays a pivotal role in facilitating the transfer of water from the flow channels to the catalyst layers while concurrently aiding in the removal of oxygen bubbles generated within the catalyst layer. We will systematically explore both novel PTL structures and the wettability of PTLs to enhance the overall performance of electrolyzers. Our research approach will encompass electrochemical evaluation and neutron imaging of the PTLs, providing valuable insights into the impact of PTL characteristics on device performance and water management.

Acknowledgement

This research is supported by the U.S. Department of Energy (DOE) Hydrogen and Fuel Cell Technologies Office through the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) consortium with support from technology manager Dave Peterson.

Simulations of Commissioning Experiments at The VENUS Neutron Imaging Instrument

Hassina Bilheux presenting for Matthew Frost

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The VENUS Time-of-Flight Neutron Imaging Instrument located at the Spallation Neutron Source will begin commissioning with neutrons in the middle of 2024 and has already been permitted limited operation to check the alignment of the upstream variable and fixed aperture systems. That rare opportunity has allowed us to make small corrections and include the final collimator and scraper geometries in the instrument simulation. The result is a refined instrument simulation that can be used to anticipate performance of the complete beamline using digital replicants of samples that have already been quantified at other neutron instruments. Results will be presented that show how the instrument is expected to perform under planned commissioning experiment conditions, as well as simulations of anticipated experiments for inspiration by future users.

Neutron Grating Interferometry User Interface - Angel 2.0

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Neutron grating interferometry (nGI) is an advanced neutron imaging technique that probes small angle scattering of neutrons and the phase shift of the neutron wavefront in addition to attenuation contrast. Scanning the grating positions produces a sinusoidal neutron intensity pattern on each pixel. This patter's amplitude or phase offsets carry the information on neutron scatting or phase shift respectively. Neutron transmission radiographs are also measured. A software analysis suite was developed to evaluate and review nGI data. The software suite is optimized for ease of use for inexperienced and new nGI users and efficiency for power users. This software suite consists of a set of libraries and a graphical user interface (GUI), implemented in Python, to perform the analysis of nGI data. An international collaboration allowed this tool to be adapted to the ORNL imaging beamlines. The new user interface will be presented in this poster, and future work will be listed.

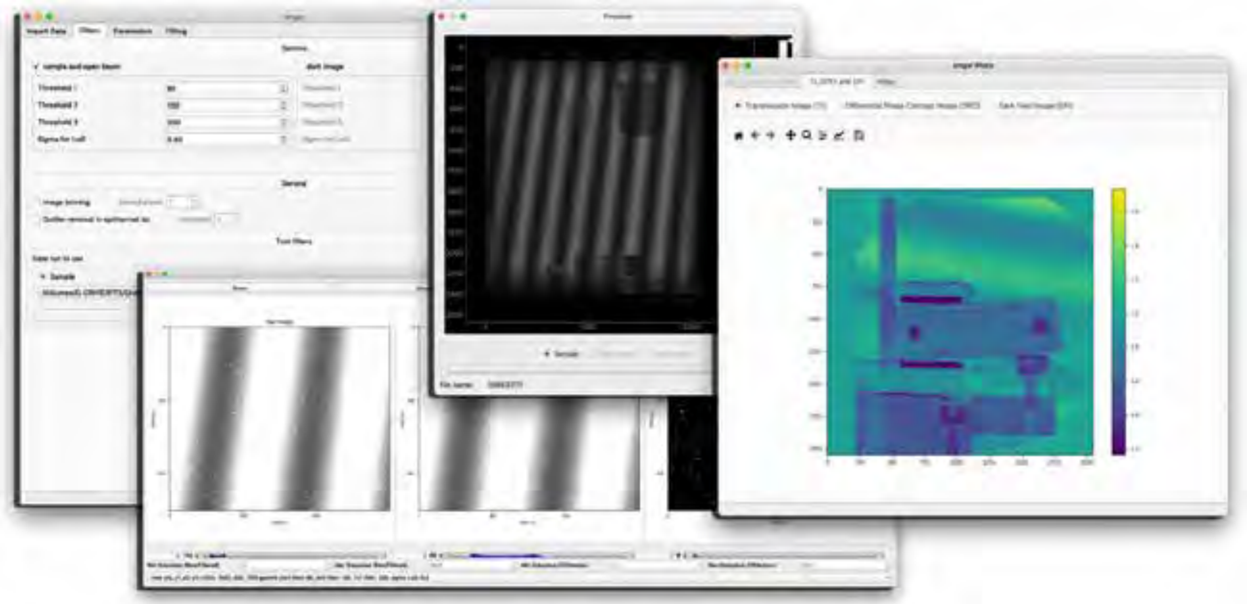

Figure caption: Screenshots of the Angel General User Interface 2.0.

A portion of this research used resources at the High Flux Reactor, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.

Beam Characterization of IMAT at ISIS After Upgrade of the Liquid H_2 Moderator

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IMAT (Imaging and MaTerials science) is a neutron imaging and diffraction instrument located on target station 2 (TS2) of the pulsed neutron spallation source ISIS, UK.[1,2] In addition to attenuation based neutron radiography and tomography, the pulsed beam from the spallation source enables energy dispersive (Bragg edge) imaging as well as time-of-flight diffraction. TS2 is currently undergoing an upgrade of its cold (18 K) liquid hydrogen moderator which will affect several instruments including IMAT. The moderator renewal involves an increase of the thickness of the moderator vessel and improved alignment with respect to the tungsten target. The instrument performance of the new setup was simulated using McStas. Characterization of the beam includes measurement of the neutron flux, spatial and beam uniformities, and spatial resolutions for different L/D collimation ratios.[1,2] The changes of the moderator are not expected to affect pulse widths over the IMAT wavelength range. Bragg edge and Bragg peak line profiles from standard samples before and after the upgrade will also be presented. [1,2] The upgrade is expected to result in a 25% increase in flux for the longer wavelength range enabling faster neutron radiography, tomography and energy-resolving experiments at IMAT.

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Simulated Design of a Laser-Driven Neutron Source Using Measured Ion Beam Energy and Divergence

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Neutron sources are attractive for radiography due to their high penetration and significantly different interaction cross sections relative to x-rays, protons, and electrons. We have begun development of a laser-driven neutron source with initial experiments at Omega EP characterizing the proton and deuteron sources. These ions will serve as the pitcher in a pitcher-catcher setup, where ions from the pitcher produce neutrons via nuclear reactions within the catcher. Shots were conducted using CD films (500 nm) and foams (20 μm, 25 mg/cm^3), providing data to compare against our previous modeling study [1] and similar experiments [2]. Ion beams were characterized using a Thompson parabola and the PROton Beam Imager and Energy Spectrometer (PROBIES) [3]. Results indicate foils produce significant deuteron flux up to the 20 MeV filter cut-off energy, as well as protons exceeding 50 MeV. Proton acceleration appears to dominate for the foam targets, with similar energies and higher flux relative to the foils. These measured ion energy and angular distributions were used as input for MCNP modeling to begin design of the catcher for neutron generation experiments. With neutron flux not yet demonstrated as being sufficient for point projection radiography at Omega EP, our designs attempt to optimally convert both protons and deuterons to neutrons, while also using D-D fusion to maximize forward flux [4].

References:

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Thermal Neutron Radiographic Imaging Results at Adelphi Technology and LSU

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Introduction to the Adelphi Technology fast (2.5 MeV DD and 14 MeV DT) neutron sources and moderated thermal neutron sources. Presented are recent applications in the areas of fast and thermal neutron radiography and tomography, Gamma Neutron Activation Analysis (PGNAA), boron neutron capture cancer therapy (BNCT), and Associated Particle Imaging (API).

In particular, are presented unpublished radiographic imaging resolution and contrast results, using a pulsed Adelphi thermal neutron source (DD110M) and time of flight imaging camera gated intensifier/CCD (Princeton Instruments PI-MAX:2048f) at Adelphi Technology.

Also presented are results of thermal neutron radiographic imaging experiments with an Adelphi DD110M neutron generator at LSU using grating optics, applied to imaging plant roots in soil and small angle neutron scattering.

Simulation and Reconstruction of 4D Neutron Dark Field Tomography Phantoms

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Many of the compelling physical phenomena that can be captured by neutron tomography necessitate additional characterization along extra dimensions (autocorrelation length, wavelength, time, etc.). These image contrast modes can elucidate small angle scattering, crystal structure, and stochastic phenomena, but often require both compromises in signal-to-noise-ratio to sample along the extra dimension(s) as well as complex data analysis routines. Simulation of datasets that model these phenomena can aid in experiment design and data analysis particularly for model based tomographic reconstructions and segmentation. This poster will highlight results for simulations of neutron dark field tomography with two specific focuses: 1) experiment-specific macro geometries and 2) automated generation of bulk datasets for preparing segmentation models. The former is achieved by voxelization of user-drawn stereo lithograph (STL) meshes to create regions of interest with seeded homogeneous microstructure. The bulk dataset generation is achieved by seeding a voxelized scene with a set of microstructures that span a pre-defined parameter space using quasi-Monte Carlo sampling. The scenes are then forward projected, convolved with a blurring kernel that is informed by the instrument geometry, modulated with a Moiré fringe, and supplemented with noise before reversing these steps to generate the synthetic dataset. Computational challenges, dose reduction, image quality, and extrapolation to other neutron imaging modes will also be discussed.

Neutron Imaging to Estimate Water Potential Gradients Across the Rhizosphere of Transpiring Plants

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Plants need to maintain hydraulic continuity between the soil and their roots to meet the transpiration needs. In wet environments, roots are typically the limiting factor for water uptake, whereas in dry conditions the soil itself becomes the limiting factor. The hydraulic properties of the rhizosphere become particularly influential when soil and root hydraulic conductivities are comparable. Although research has shown that the rhizosphere has different properties to the bulk soil, its effect on root water uptake is not fully understood. This gap is partly due to the lack of methods to measure water potential gradients in the rhizosphere of transpiring plants.

To fill this knowledge gap, we used time-series neutron radiography. This technique allowed us to detect small variations in water content and potential between bulk soil and root cortex at different soil moisture and transpiration levels. We grew maize seedlings in aluminium rhizoboxes filled with two substrates, sand and loam, and subjected them to controlled water stress. We performed scans both at night, to capture conditions when the root and soil were in equilibrium (due to low transpiration), and during the day under LED lighting to simulate transpiration.

At the same time, we measured transpiration rates and stomatal conductance. By analysing the radiographs together with water retention curves obtained from similarly grown samples, we obtained a calibration curve relating water content to water potential in both bulk soil and root cortex. This approach allows us to measure the magnitude of water content and water potential gradients in the soil, determine the stomatal response to these gradients, and assess the role of both soil and roots in regulating transpiration.

New High Pressure Sample Environment on DINGO

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A newly emerging research area is the observation of temporal structural changes when materials are put under loads at high temperature. Neutron tomography allows the 3D and 4D visualisation of processes in geoscience on the microscale. Studying the behaviour of rock formations under gas and / or liquid pressure is of global interest in oil and gas mining as well as water management or carbon capture settings. All these processes are important for applied sciences and the industry and our unique sample environments allow us to study these processes using neutron tomography under high gas pressure (100 MPa), fluid flow through the sample and uniaxial mechanical load.

The newly developed cell is designed to analyse samples with maximum of 26 mm diameter and 100 mm length.

We will present first results flooding Marcellus Shale samples with 100 bar methane and subsequent 200 bar compaction in the absence of methane. In a third step we pressurised the compacted sample with methane again. For each step a full tomography has been taken, visualising the methane distribution in-situ.

In a second application we present the formation of fluid channels in rock formations as a result of water injection into the system. The experiment was combination of time-lapse radiography and tomography.

These examples show that we can visualise natural and synthetic materials under exposure to reactive fluids, uniaxial and triple axial stresses.

The existing system will be upgraded to host corrosive gases as well as hydrogen. The temperature can be varied between 0°C and 700°C in its final stage and is planned to be available for the user program in early 2025.

Preliminary Design Study on Neutron Imaging Facility in New Research Reactor in Japan

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The new research reactor will be constructed at the site of the fast breeder reactor Monju, which the Japanese government had decided to decommission. It aims to become a core center for research and development in the new nuclear field and human resource development in Japan. Neutron imaging is one of the most important parts of the technology for this purpose. In neutron imaging, the main neutron energies used are thermal and cold neutrons. Thermal neutrons generally have a higher transmission characteristic than cold neutrons. On the other hand, cold neutrons are easier to control optically than thermal neutrons. Since each measurement has different characteristics, it is desirable to install independent experimental apparatuses for thermal and cold neutrons in the new research reactor. The thermal neutron imaging facility has been selected as one of the five priority facilities in the new research reactor. It features high-speed imaging, 3-dimensional computed tomography, and operand measurement using actual equipment with short exposure time using a high-intensity, large-area beam. In addition, the sample area should be large enough to accommodate large objects such as industrial products, with a view to industrial applications. The cold neutron imaging facility is also an important facility not only for industrial applications but also for a wide range of scientific applications, such as materials science. It features high-contrast, high-positional resolution for precise measurement and innovative imaging using phase contrast and polarization. For this reason, it is desirable to have a large area in the beam direction to allow for the placement of optics for beam control and to make the experimental setup flexible for use. At the present stage, the basic specifications of these facilities will be fixed by summarizing the user's needs and information collection of existing facilities.

Experimental Evaluation of the MURR E-Port Beamline for a New Imaging Instrument

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The University of Missouri Research Reactor Facility (MURR) is a 10 MW flux trap research reactor with 6 thermal neutron beam ports labeled A through F. The current Boron Neutron Capture Therapy (BNCT) facility located at beam port E is in the planning stage to be upgraded to support a thermal neutron imaging facility. MCNP modeling of the neutron brightness shows this port to have similar brightness to the NIST BT-2 Neutron Imaging Facility. As an experimental check NIST and MURR performed a joint evaluation of this beam (Figure 2) by performing fluence rate evaluation with a NIST neutron imaging camera, an L/D measurement using 25 μm thick Gd foil and an evaluation of the source spatial (x-y) stability, which is important for high resolution imaging. In addition, tomography of an 18650 lithium ion battery was performed. The results of this evaluation will be presented along with a discussion of suitability of this beam line for the use as a neutron imaging facility.

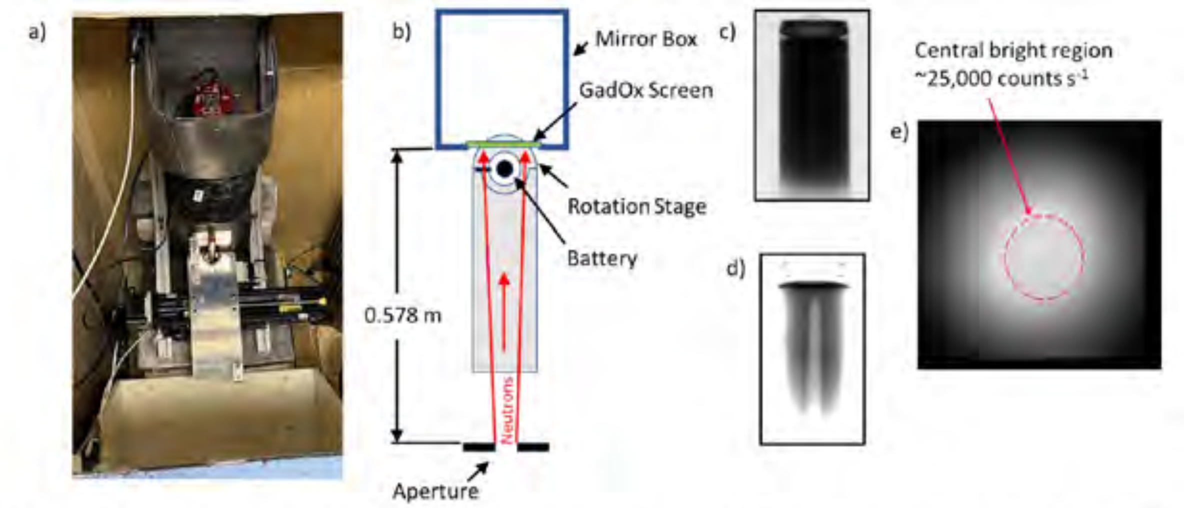

Figure 1. Experimental setup is pictured in a) and shown schematically in b). The neutron aperture is 4 cm in diameter. The neutron scintillator is a 20 μm thick Lexel Imaging Systems Gadox:Tb screen†. A mirror box couples the digital camera, which is a ZWO ASI1600mm CMOS (4656×3520, 3.8 μm) with a Nikon Nikkor 50 mm f/1.2 lens. The reproduction ratio is 7.9. The resulting effective pixel pitch is approximately 30 microns. The transmission image of an 18650 lithium ion battery is shown in c) and contrast enhanced to show how the central hollow section of the battery is visible. The overall intensity at this position is shown in e) where there are 25,000 counts s^{-1} in a 30 micron pixel.

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†Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

Streamlining Porous Media Experiments: A Test Stand for Neutron Imaging

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Conducting experiments on porous media via neutron imaging techniques often encounters logistical and technical hurdles, impeding research progress and beamline efficiency. To mitigate these challenges, we propose the development of a comprehensive test stand to provide a standardized and robust infrastructure for porous media experimentation.

Motivated by the frequent need for users to bring their equipment to our facilities, our initiative seeks to streamline experimental setup procedures and enhance user accessibility. Currently, users often spend considerable time building and verifying their equipment, which delays research progress and contributes to suboptimal beamline utilization, particularly given our high overbooking rates. Moreover, concerns regarding material activation and subsequent inability to retrieve samples further underscore the need for a standardized experimental setup on-site.

Our proposed test stand caters to three primary experiment concepts: evaporation, imbibition, and rainfall infiltration. These concepts represent diverse research requirements and necessitate specialized experimental setups. The test stand architecture addresses various critical components essential for seamless experimentation:

Flexibility in sample handling is ensured through adaptable sample containers and holders, accommodating different shapes and dimensions commonly encountered in porous media research performed at PSI. The holders provide an experiment interface to different pump solutions for precise fluid control and balances to monitor the in and out flow to the sample. Implementing slip-ring technology on the existing turntable enhances experimental versatility and functionality by allowing multiturn tomography scans without entangling the connected wires and tubes. In particular, one balance is installed on the tomography turntable to allow tracking of the sample weight during an ongoing experiment. Pumps and balances are integrated into the instrument control system, NICOS. Integrating these devices into the control system has the benefit of more precise experiment control and direct logging of the sample status, which is stored as a part of the metadata registered with each image. The system is further complemented with comprehensive sensor logging capabilities, facilitated by a multi-channel sensor logging device compatible with various sensor types, enabling in-depth data acquisition and analysis, encompassing parameters such as temperature, moisture, and flow.

In conclusion, our proposed test stand offers a standardized and efficient platform for porous media experiments, addressing logistical challenges and optimizing research workflows. By enhancing experimental accessibility and efficiency, this initiative aims to advance the field of neutron imaging and porous media research.

Water Flow and Microplastic Distribution in Sandy Soils Quantified with Neutron and X-Ray Imaging Methods

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Soil is the largest sink of microplastic (MP) in terrestrial ecosystems, yet little is known about the transport of MP in soils and its effect on water flow. MP is potentially hydrophobic, and the transport of MP and water flow are closely linked. However, the extent of MP transport in soils and the interactions with water dynamics remain largely unclear. We applied neutron and X-ray imaging methods to investigate water dynamics and distribution of MP (PET, 20-75 µm) in sand (700-1200 µm). Simultaneous neutron and X-ray CT were used to monitor MP distribution in different contents and time-series neutron radiography to image water distribution during repeated wetting and drying cycles. The imaging revealed that MP reduced water infiltration. High MP contents induced local water repellency and were by-passed by percolating water. MP affected the vertical distribution of water, reducing the local soil water content and driving water to deeper soil layers. Rapid and preferential infiltration into deeper areas of the sample as well as lower local volumetric water contents above the wetting fronts were observed. Alteration of water flow were MP content dependent. Significant transport of MP was not detected during the wetting and drying cycles, plausibly because water by-passed the pore space containing MP. Transport porocesses like advection, which are significant for wettable particles, play only a minor role on transporting low wettability particles, like MP, under unsaturated conditions. In conclusion, the interactions between MP and water impact the infiltration of water, with several implications for the retention and fate of MP in soils.

Neutron Imaging and Tomography Facility at the MIT Nuclear Reactor

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A detector upgrade has been installed and tested at the thermal neutron diffraction/neutron imaging beamline at the MIT Nuclear Reactor Laboratory. The beam flight length and cadmium aperture were optimized to achieve a L/D ratio of up to 520. Neutron flux at the sample position is about 2×10^6 n/cm^2/s at L/D = 320. The new detector consists of a mirror box, ZWO ASI1600MM Pro cooled CMOS camera, Nikon Nikkor 85mm f/1.4G lens with PK13 extension ring, and a 3.75 in by 3.75 in active area, 20 µm thick P43 scintillator. The camera and lens configuration gives an effective pixel size of 8.74 µm with a real resolution around 30 µm. The sample can be installed on a rotation stage for tomography with typical acquisition times of 24 to 48 hours. Fig. 1 shows an example of tomographic imaging of a 3-D printed stainless-steel object, a model of the MIT dome. Figure 2 shows tomographic images of three different "neutron friendly" lithium-ion batteries. Neutron tomography improves the ability to see lithium plating during battery cycling, and so to optimize the materials composition. Other previous projects included imaging of irradiated hydride fuel rodlets, in-situ radiography of electrolyzer cells, and dynamical imaging of water boiling. This poster will give an overview of improvements made to the beamline as well as several examples of research currently being performed at MIT.

Figure 1. Tomographic projections of a 3-D printed model of the MIT Dome structure. The model is made of stainless steel and is 1" in diameter.

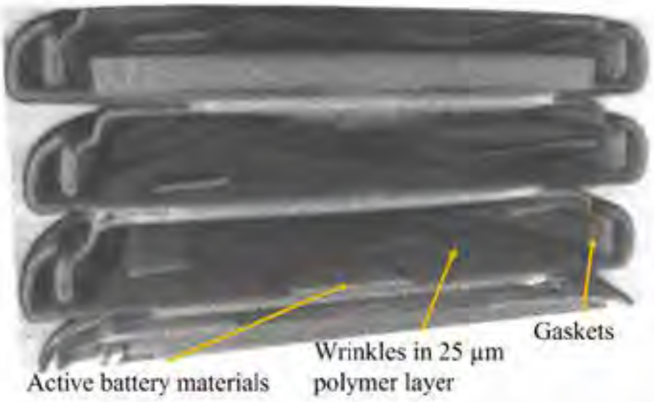

Figure 2. Tomographic images of 3 "neutron friendly" lithium-ion batteries. The use of PFA gaskets over typical polypropylene gaskets makes resolving active materials much easier.

Radiography Using a Neutron Ray Source Containing Gamma Rays

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There are very limited neutron sources used in industry, the most representative sources being Cf-252 and Am241/Be sources. Among them, the half-life of the Cf-252 source is about 2.65 years, which is not long. In the case of the half-named Am241/Be crew, it has a long lifespan of 432.2 years, making it economical. Additionally, since gamma rays of various bands are also emitted, more detailed pictures can be obtained than radiography using a single neutron spectrum. In this paper, we will discuss radiography using the Am241/Be source.

Introduction of Camera System for CNRF at JRR-3

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The CNRF is a neutron radiography facility using cold neutrons installed in the beam hall of JRR-3 (Fig. 1). A neutron beam, guided from the JRR-3 reactor room to the beam hall by a C2 cold neutron guide tube, is split into three beamlines (reflection angles 0°, 10°, and 20°) using a neutron bender [1]. The CNRF uses that with the reflection angle of 20°, C2-3-3-1 port. The CNRF imaging position is approximately 4 m from the bender, and the beam size is 20 mm (W) × 30 mm (H). The neutron flux at the position is approximately 1.7×10^7 n/cm^2/s. Figure 2 shows a photograph of the inside of the CNRF imaging room. The imaging room size is approximately 650 mm (W) × 850 mm (H) × 600 mm (D). A rotary stage and a linear stage for samples are equipped in the room.

At the resumption of JRR-3 operations in 2021 after a 10-year shutdown, only an imaging system using imaging plates (IPs) was available at the CNRF. Although high-resolution images could be acquired, the system was unsuitable for continuous imaging required for computed tomography (CT) scans and dynamic imaging. It was also difficult to perform quantitative analysis from the images. To resolve these problems, we have introduced a new imaging system with a dark box, a scintillator, and a CMOS camera (Hamamatsu Photonics, ORCA Flash 4.0 V3). In this poster, the performance of the imaging system, usage examples of the CNRF, and its results will be presented.

Fig. 1. Photo of the CNRF experimental space.

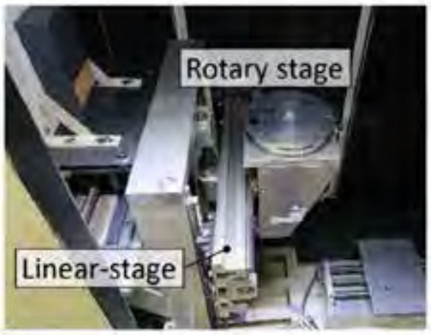

Fig. 2. Photo of the CNRF imaging room.

References:

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Recent Evaluations of Scintillators and Phosphors for Fast Neutron Imaging

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Scintillators or phosphor-coated substrates (also called scintillators herein) are typically used to convert collimated fast neutrons to visible light for optical imaging. This may be used as the imager for neutron radiography or for neutron-source imaging if used with a neutron aperture. Twenty-seven scintillator-substrate combinations, shown in the table below, were used in a radiographic configuration at the Los Alamos Neutron Science Center (LANSCE, specifically WNR-60R) to evaluate their potential brightness, signal-to-noise ratio (SNR), spatial resolution, relative sensitivities to photons, and decay times. These parameters were chosen to inform future imager-design decisions. Parameters were calculated from images collected using three time-of-flight (ToF) windows: photons only, 14 MeV neutrons, and 1-5 MeV neutrons. Radiographic transfer curves of tungsten and tantalum steps with thicknesses ranging from 1-60 mm were also measured for each ToF window with each scintillator. Results are forthcoming. Methods and results will be presented and tradeoffs will be discussed.

Table 1. Scintillator configurations tested.

Vendor	**Scintillator**	**Dimensions [cm]**	**Converter layer**
Saint Gobain	BC412	15×15×1	None
Eljen	EJ200	15×15×3	None
LLNL	HiLY	10×10×1	None
SNL	OGS	10×10×1	None
Fairfield	ZnS	3.5×0.3	None
RC Tritec	ZnS:Cu + PP	15×15×0.4	None
NNSS, PhosphorTech	ZnS:Ag	10×10×0.01	Polystyrene 1.59 mm
NNSS, PhosphorTech	ZnS:Ag	10×10×0.01	Polystyrene 2.38 mm
NNSS, PhosphorTech	ZnS:Ag	10×10×0.01	Polystyrene 3.175 mm
NNSS, PhosphorTech	ZnS:Cu	10×10×0.01	Polystyrene 1.59 mm
NNSS, PhosphorTech	ZnS:Cu	10×10×0.01	Polystyrene 2.38 mm
NNSS, PhosphorTech	ZnS:Cu	10×10×0.01	Polystyrene 3.175 mm
NNSS, PhosphorTech	$(Sr,Ba,Ca)SiO_4$:Eu	10×10×0.01	Polystyrene 3.175 mm
NNSS, PhosphorTech	$(Sr,Ba,Ca)SiO_4$:Eu	10×10×0.01	Black HDPE 3.175 mm
Hilger	CsI:Tl	10×10×1	Black HDPE 3.175 mm
Hilger	CsI:Tl	10×10×1	White HDPE 3.175 mm
Hilger	CsI:Tl	10×10×1	Polystyrene 1.59 mm
Hilger	CsI:Tl	10×10×1	Polystyrene 2.38 mm
Hilger	CsI:Tl	10×10×1	Polystyrene 3.175 mm
Hilger	CsI:Tl	10×10×1	None

Additional phosphors with abbreviated testing: $Sr_2P_2O_7$:Eu, $BaMgAl_{10}O_{17}$:Eu with LiF, $Gd_3AL_2Ga_3O_{12}$:Ce, LuAG:Ce, $Y_3(Al,Ga)_5O_{12}$:Ce, $(Y,Gd)_3Al_5O_{12}$:Ce, and $(Sr,Ba)SiO_4$:Eu.

Utilization of Fast-Neutron Imaging in Industrial Applications

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Fast neutrons have much larger penetrating ability than thermal neutrons as well as X-rays. Its penetration ability will be able to use for identification low-Z materials in the elemental composition materials.

For utilization of fast-neutron imaging technique in industrial applications, a study on

performance evaluation of fast-neutron imaging has performed with a variety of neutron sources as a tokamak with D-D plasma, a fission reactor, and a D-D neutron generator. The performance evaluation were done with fast-neutron transmission imaging and tomography techniques for a variety of neutron sources by means of a scintillator based CCD camera device.

Fast-neutron imaging techniques can be considered as a complementary technique to X-ray imaging if the composition of the sample requires visualization of light materials in the presence of high-Z materials for industrial applications. Details will be presented.

Review on Digital Neutron Imaging

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The transition from analogue, film-based detection methods to digital ones in the middle of the last decade of last century can be evaluated as a real “revolution” from the present point of view. Even if film methods are practiced until now for selected, certified applications (e.g. for space launcher component inspections), the majority of facilities word-wide are equipped with one or more digital detection systems.

The development of digital CCD cameras with low noise and high efficiency enabled exposure times in the order of minutes, which was needed for the registration of the very low light emission from neutron sensitive scintillators screens. The most relevant limitation is by now the relative low neutron flux intensity at all imaging facilities. PSI in collaboration with TU München were pioneering this technique at their facilities at SINQ and FRM-I and FRM II and performed first tomography studies this way [1]. There was a steep learning curve in optimization of scintillator emission wavelength to match CCD sensitivity, different types of CCD (front and back side illuminated) and later CMOS sensors, optical lens and mirror systems and software development.

Digital detectors were not only linear, as opposed to film, but allowed for digital image processing as normalization to beam intensity, and computed tomography. Digital amorphous silicon detectors were tried as well by replacing or adding of neutron sensitive detection materials (Gd, Li-6), but internal data preprocessing and fixed field of view made them much less flexible compared to camera-based systems.

Pixel arrays, placed directly into the beam have been developed with the Medipix/Timepix chips, combined with image intensifiers, which allow for time-of-flight applications, however with small FOVs.

Twenty years later, camera-based systems are most commonly employed in neutron imaging, supported by newly developed low-price but high-resolution astronomy cameras, with very large pixel numbers and high sensitivity. With camera systems, fields-of-view (1 cm to 40 cm) can be adapted, and correspondingly the spatial resolution. Furthermore, image rates up to 100 Hz can be employed for dynamic studies.

A lot of development was done on neutron sensitive scintillator screens both for thermal/cold and for fast neutrons, according to mixture of scintillating material and neutron absorbing material, but also emission spectrum and decay times, spatial resolution, gamma insensitivity.

One of the latest approaches is the registration of single events in neutron interactions, which enables to distinguish “valid” and disturbing contributions to the neutron image. This method is mainly based on very high readout performances, high data throughput and enormous storage capacity.

The upcoming imaging facility ODIN at the European Spallation Neutron Source (ESS, Lund) will provide some other challenges - the best utilization of the pulse beam. This can only be managed by digital systems, while their kick-off dated back now about 25 years ago.

[1] B. Schillinger et al., doi:10.4028/www.scientific.net/SSP.112.61

Study on the Visibility of Organic Materials Within Metallic Covers, the Pseudo-Buddha

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The combination of metals and organic materials can be found in many studies of objects with relevance to cultural heritage. Prominent examples are bronze sculptures from Buddhist Tibetan regions, often many centuries old.

It was found in comparative studies, that neutron imaging methods are preferred in non-invasive investigations of the hidden content over X-ray ones due to the opposite contrast mechanisms of these both techniques [1]. Based on this experience, we have investigated nearly a hundred prominent samples of this cultural region with great success [2].

Nevertheless, it was claimed that also X-ray methods are able to provide similar results, when the right X-ray energy is chosen, and the dynamic range of the detection system is set adequately.

Because the NEUTRA/XTRA facility at SINQ, PSI, allows for both thermal neutrons and X-ray imaging studies with the same detection system, a systematic investigation was initiated to find out if and when organic materials can be visualized within a metallic (copper) cover. Several arrangements of typical organics, which are also found in real Buddha bronzes, were selected and investigated.

First, we imaged the “pure” samples without the Cu - cover by thermal neutrons and 180 kV X-rays (and 1 mm beam filter). Later, we surrounded the samples with cylinders of 1 until 10 mm wall thickness, sequentially.

The results are shown in the poster as a comparison of the different contrasts by the two kinds of radiations, obtained with the same detection system.

As expected, the visibility of organic materials goes drastically down in the X-ray case, when the samples are covered by the Cu shielding. After a wall thickness of 5 mm, means transmission through 10 mm Cu, no signal was available from the organic content. On the other hand, even 10 mm wall thickness of Cu doesn’t shadow in the neutron case the signal from the organic materials too much and their visibility is still valid.

In conclusion, we can state that very thin wall thickness of sculptures on the order of one mm might enable to visualize some content of such samples also with X-rays. However, the quality of the X-ray data are very limited compared to those obtained with neutrons. In some limited cases, also the combination of neutron and X-rays might bring best synergetic results.

[1] E. Lehmann et al., doi.org/10.1111/j.1475-4754.2009.00488.x
[2] E. Lehmann et al., doi.org/10.1007/978-3-030-60016-7_11

CORINT -- An Interdisciplinary Research Project on Corrosion Phenomena and Multi-Modal Tomography

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The corrosion processes of metals embedded in opaque porous media (e.g., soil or concrete) are omnipresent but still poorly understood. A better understanding of such processes would be crucial for progress in various application areas, such as archaeology (excavation of historical finds), conservation, civil engineering (steel-reinforced buildings and constructions), and nuclear waste disposal. Traditional analytical methods are often invasive or destructive and limited in providing insight into corrosion dynamics without altering the sample and its environment.

We present the CORINT project, which aims to enhance the understanding of hidden corrosion processes by combining the non-destructive methods of X-ray and neutron tomography, taking advantage of their complementary behavior. CORINT is an interdisciplinary research project funded by the Swiss National Science Foundation that unites researchers from different Swiss universities, museums, and institutions. The project name is an acronym from the project title: “ELUCIDATING CORROSION OF IRON IN POROUS MEDIA BY NEW QUANTITATIVE MULTIMODAL IN-SITU TOMOGRAPHY”.

The project objective is to advance combined X-ray and neutron tomography specifically for studying the corrosion of metal objects in opaque materials. The optimization and tailoring of this bimodal approach towards the specific question will allow us to non-destructively monitor concealed corrosion processes and dynamics in an undisturbed state. For the first time spatially resolved quasi-in-situ investigations of metal corrosion processes within opaque porous media will be possible.

This is particularly interesting as traditional approaches (e.g., analytical techniques for identifying corrosion products, excavating archaeological objects, etc.), generally require exposing the metal and removing the porous medium.

In the course of the project, it is furthermore planned to integrate additional information acquired with conventional (e.g., electrochemical techniques) and more innovative (e.g., muon-induced X-ray emission) methods to the information obtained by neutron & X-ray tomography. Combining information from this broad variety of sources will result in a truly multi-modal approach considering as many aspects as possible. If the project is successful, the new approach might be a breakthrough in addressing corrosion questions related to steel and iron in porous media.

Analysis of the Noise Limit in Neutron Dark Field Data

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Understanding the influence of noise present in measurements is crucial to correctly interpret the acquired data. Mainly, a quantitative analysis of measured properties is influenced by noise. In this contribution, we will demonstrate how Poisson noise present in neutron grating interferometry (nGI) experiments leads to a distortion of quantitative measurements. Here, we present the necessary simulation model and its experimental verification.

NGI generates an interference pattern. Scanning this pattern leads to an intensity oscillation in every pixel of the detector. Attenuation, phase-shift, and ultra-small-angle scattering (USANS) in the sample locally influences the intensity oscillation. USANS causes a decrease in the visibility of the intensity oscillation. The dark field image (DFI) maps the visibility change and contains information about, e.g., the magnetic domain structure of a ferromagnet or lack of fusion defects in additively manufactured steel samples. The visibility decreases towards zero for strongly scattering samples. However, the Poisson noise inherent to neutron detection causes variations during an nGI scan. These variations ultimately result in a finite minimum DFI. Effectively, a part of the DFI range is not accessible. For a quantitative evaluation, this distorts the measured size of the microstructure.

We will show how neutron statistics and the quality of the nGI setup influence the minimum visibility and define a dynamic range for the DFI. Fig. 1 shows the dependence of a) the minimum visibility and b) the dynamic range of the DFI on the detected neutrons. This dynamic DFI range determines the amount of scattering tolerable for quantitative measurements, which is essential for planning any quantitative nGI measurements.

Film-Based Transfer Method Neutron Radiography Post Irradiation Examination of Irradiated Nuclear Reactor Fuels

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NRAD, the Neutron Radiography Reactor located at the Idaho National Laboratory (INL), provides researchers with images of irradiated nuclear fuels for post irradiation examination (PIE) using the nondestructive technique of neutron radiography. Past, present, and future reactor fuel designs of varying geometries are routinely examined for behavioral characteristics after irradiation. Typical behaviors of interest include cracking, swelling, migration, voids, and changes in density.

Transfer method neutron radiography is performed at NRAD for irradiated fuels. Dysprosium and cadmium-filtered indium conversion screens (foils) are activated, then coupled to industrial X-ray film where the decay radiation from the foils exposes the film and provides radiographs from thermal and epithermal neutron energies, respectfully. The film is developed with a commercial photo processor, interpreted by a certified neutron radiographer, and then digitized with a high-resolution flatbed scanner. The digital images are transmitted to the researcher as a record copy.

Advancements in neutron imaging technology such as computed radiography (CR), digital radiography (DR), and three-dimensional tomography have made transfer method neutron radiography of irradiated fuels faster, more efficient, and relatively cost effective compared to film-based solutions. However, film remains the standard baseline comparison to these newer technologies and a method for image resolution verification at NRAD.

The challenges associated with imaging highly irradiated samples require the time tested and proven transfer method neutron radiography for PIE. Specimens of never before seen nuclear reactor fuels are radiographed to visually examine fuel behavior from irradiation. This nondestructive examination technique does not determine acceptance/rejection of a specimen, but rather whether or not the resulting radiograph is acceptable based on the techniqueâ€™s execution.

NRAD’s imaging capabilities include film, CR, and digital neutron radiography. This poster describes the use of film as a necessary baseline for neutron imaging technology comparisons and qualifications. When a new or different capability is explored at NRAD, the images are compared to film to resolve the limits of the technique’s resolution. Image quality indicators and specimen sample standards are created and imaged for a quantitative comparison. The resultant images are then interpreted by an American Society for Nondestructive Testing (ASNT) certified level III neutron radiographer to determine artifacts and/or discontinuities, and to evaluate beam quality and image resolution.

Neutron Imaging in Your Own Lab

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To bring the benefits of neutron imaging to the local laboratory, we have started imaging experiments with a fusion neutron generator as a source. With a flux many orders of magnitude weaker than a reactor, ingenuity is required to make good-quality images.

Key is the imaging detector, which has to feature the best detection efficiency you can get. We use a detector we developed, based on neutron-sensitive microchannel plates (MCPs). We will explain the principles and design of the detector, and show some results.

We will show first results of imaging using a deuterium-deuterium fusion generator as a source, proving the feasibility of this type of instrument. And we will outline our plans and ambitions for the near future. This development will democratize the use of neutron imaging, and make it available to users in industry.

Steel pen: photo neutron image X-ray image
(taken with a generator source)

Pulsed Neutron Imaging Activities at the Hokkaido University Neutron Source, HUNS, in 2023

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Hokkaido University Neutron Source, HUNS, has short-pulsed cold/thermal/fast neutron sources and a mega-electronvolt X-ray source driven by 32 MeV-3.2 kW electron linear accelerator [1]. The facility was built in 1973, the accelerator was replaced in 2018, and the electron transport tube was replaced in 2020. In addition, the facility building will be renewal in 2024. The cold neutron source is a coupled-type 20 K solid methane moderator, and is used for the TOF small-angle neutron scattering (TOF-SANS) instrument. The thermal neutron source can be changed between coupled-type and decoupled-type of 300 K polyethylene moderator. The thermal neutron source is used for developments of neutron optical devices and detectors. The coupled-type thermal neutron source is used for epithermal neutron resonance absorption imaging. The decoupled-type thermal neutron source system with a supermirror guide tube and a grid collimator is used for high wavelength resolution and low background Bragg-edge neutron transmission imaging [2], and is utilized for materials science, industrial applications and international collaborations of steels, batteries, nuclear materials, cultural heritages, thermography and so on. X-ray imaging system and machine learning techniques sometimes assist neutron imaging. The fast neutron source, a Pb neutron production target, is used for acceleration experiments of cosmic-ray neutron-induced single event effects of semiconductor devices. Furthermore, recently, new collaboration works on beam irradiation are developing and planning for astrophysics, medical biology and space engineering. For pulsed neutron imaging activities in 2023, steel microstructure study by Rietveld-type Bragg-edge transmission spectrum analysis with SEM-EBSD [3], crystalline phase fraction imaging of TRIP steel by double Bragg-edges analysis [4] and thickness imaging of corrosion product on steel by Bragg-edge analysis with hydrogen incoherent scattering effect [5] are highlight topics at HUNS. In this poster, these featured topics will be reported.

[1] https://www.eng.hokudai.ac.jp/labo/QBMA/LINAC/index-e.html
[2] H. Sato, M. Sato, Y. H. Su, T. Shinohara and T. Kamiyama, ISIJ Int. 61 (2021) 1584.
[3] M. Bakhtiari, F. Sadeghi, H. Sato, W. Um, C. H. Yim and H. S. Lee, J. Appl. Crystallogr. 56 (2023) 1403.
[4] H. Sato et al., ISIJ Int. (in preparation)
[5] G. Ishikura, H. Sato, R. Kitagaki, T. Kamiyama, D. Oh and Y. Yoda, Constr. Build. Mater. (submitted)

Guidelines for Neutron Imaging Facility Design

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Neutron imaging had a breakthrough when electronic camera detectors became available 30 years ago, which allowed for electronic image processing, but also for sacrificing intensity for higher resolution and sharper images. Detectors have become so sensitive that neutron computed tomography can be performed at 500 W (!) reactor power, and installations are now possible at low-power research reactors that have been regarded as insufficient until recently, but such use requires an optimal design of the neutron beam for imaging. No single article exists that describes 30 years of experience in facility design. This poster tries to give an overview about lessons learned. It will not save a new user from looking up many references, but it highlights hidden, but crucial details that are essential for a good imaging facility – but it will also treat crucial mistakes in shielding and instrumentation which may seem logical at first sight, but can make a facility next to unusable. The poster will also mention where extreme diligence may be unnecessary, as it has no influence on image quality. Subjects will be facility design with collimators and shielding, detector design with different cameras and screens, and motion control.

How to Image Fast Neutrons with Thinner (Sub-Mean-Free-Path) Apertures

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Neutron imaging is a useful tool with applications ranging from material radiography for industrial and security applications to probing implosion geometries of inertial confinement fusion experiments. Pinhole arrays typically used for such imaging require thick substrates to obtain good contrast along with a small pinhole diameter to obtain good resolution, resulting in pinholes that have large aspect ratios. For example, the pinholes used at the National Ignition Facility (NIF) are machined from 20 cm thick Au, with pinhole diameters of 5-210 µm. This leads to expensive pinhole arrays that have small solid angles and are difficult to align.

Coded apertures are a form of pinhole array where multiple pinholes create overlapping projections of the source onto a detector, which then requires decoding in order to generate a reconstruction of the source shape. Here, we discuss how this decoding step relaxes the requirement of generating high contrast within the aperture while preserving high contrast in the reconstruction. We show simulations compared against the NIF imaging system, showing a reduction in aperture thickness from 20 cm to 1 cm is possible while still measuring the correct source diameter. Finally, we show results using a 3.5 mm resolution 6.8 mm thick tungsten CASPA to image the neutron source of a dense plasma focus (DPF). The LLNL MJOLNIR DPF produces roughly 10^{11} DD (2.5 MeV) fusion neutrons that have a mean-free-path of 23.8 mm through tungsten, which are typically imaged with pinholes through approximately 110 mm thick substrates. Using conventional cross-correlation decoding techniques, our reconstruction was successful in imaging a source diameter of 5.2 ± 1.8 mm, limited by the aperture cell size.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and was supported by the LLNL-LDRD Program under Project No. 22-ERD-022.

Release Number: LLNL-ABS-860239

Unveiling Magnetic Structure Information with Polarized Neutrons and Dark Field Imaging

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Neutron imaging techniques have advanced our understanding of materials, offering insights beyond just neutron attenuation. New methods like grating dark field imaging and polarized neutron imaging provide additional data. In one study, we used these techniques to examine grain-oriented electrical steel, revealing magnetic domain structures and magnetization states. By altering the setup, we could visualize domain walls. In another study on magneto-elastomers (MAE), we observed the mechanical and magnetic response of soft iron particles in a polymer matrix. Dark field images captured differences in spin polarization, showing magnetic scattering related to varying external magnetic fields. Quantitative analyses revealed different length scales for iron particles and their magnetic domains.

Our first investigation focused on grain-oriented electrical steel, deploying both polarized neutron imaging and neutron dark field contrast imaging with polarized neutrons to elucidate magnetic domain structures. The precession of the neutron spin in the material's magnetic field was quantified through a wavelength scan, revealing domains and associated magnetization states. Altering the set-up in-situ, dark field imaging with a symmetric Talbot-Lau interferometer enables to illustrate the domain walls. The two measurements are done with the sample in the same position and the features in two different images match very well.

A different method is used in the second study, which concerns magneto-elastomers (MAE), where the mechanical and magnetic response of soft iron particles linked by the base polymer material is in the focus. Dark field images for spin up and for spin-down polarization of the incident beam and a clear signature of magnetic scattering is recorded through differences in the two measurements evolving in relation to different strengths of applied external magnetic field. The attempted quantitative scattering analyses yielded different length scales for the iron particles in the polymer matrix, matching the known size, and their magnetic domains respectively.

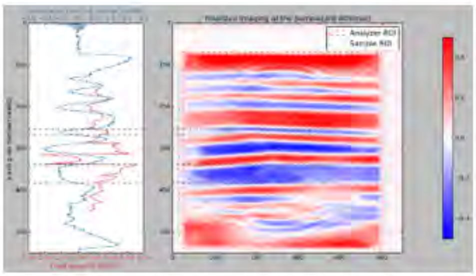

Fig. 1. Magnetic domain structures of a grain oriented steel sheet revealed by polarized neutron imaging

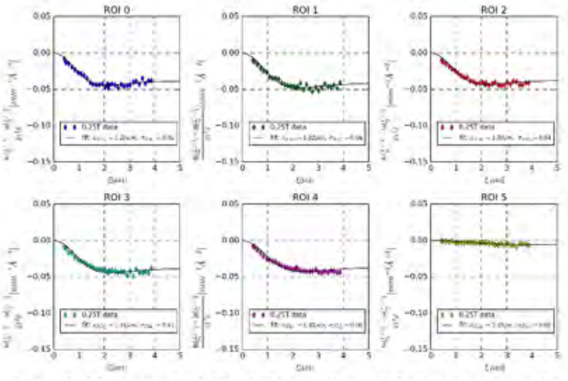

Fig. 2. Differential Dark Field Signal between Spin Up and Down of a MAE sample for different strengths of applied magnetic field. Fitted lines represent theory corresponding to magnetic SANS.

From Unrealistic Dream to Real Education in Neutron Imaging at 100 W Research Reactor VR-1 in the Czech Republic

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The Czech Technical University in Prague (CTU) operates the Training Reactor VR-1 with a nominal power of 100 W. The VR-1 reactor is typically representative of very low-power research reactors with the power of hundreds of W up to several dozen kW, which are mainly used for educating nuclear engineering students in experimental reactor physics and radiation protection. At many of these research reactors, it is considered that education in reactor physics and radiation protection are the only educational experiments that can be done on their machine.

Even though the VR-1 reactor has excellent capabilities for reactor physics experiments, the reactor design for any beam experiments was insufficient. In the early nineties, the first discussions on implementing neutron imaging clearly showed that it was only an unrealistic dream. These discussions were also held periodically in the next 15-20 years. Implementing neutron activation analysis at the reactor in 2012-2016 and successful regular, systematic education since 2020 also brought the impulse to neutron imaging.

From 2012 to 2015, the imaging experiments were part of students' bachelor's and master's theses. At that time, the first imaging experiments were also held at three other very low-power research reactors worldwide. The experiments at the reactor were homemade trials using analogue image plates and self-developing films with L/D=2-3 without any contact with the neutron imaging community. Thus, the results were insufficient to build a real imaging facility but sufficient to make the first step from an unrealistic dream to a real machine. Lessons learnt also clearly showed the need to contact the imaging community and learn from well-established facilities.

In 2020, CTU started a collaboration with the Burkhard Schillinger team from FRM-II Reactor, and with their significant help, the idea of analogue imaging was left away, and a digital imaging system NIFFLER (Neutron Imaging Facility for Learning and Research) was built in 2020-2022. Nowadays, the VR-1 reactor is one of the few very low-power reactors worldwide that can carry out 2D neutron imaging and the only reactor that carries out 3D neutron imaging. It was a huge step toward real education.

A standard imaging demonstration experiment for nuclear engineering students with well-defined pedagogical added value was developed in 2022 for three regular master courses. Nowadays, under development is an entire semester course (13 weeks, 2 hours of lectures + 3 hours of labs), which will be included in regular education starting the academic year 2024/2025.

After almost 35 years, the unrealistic dream from the nineties became reality. Education in neutron imaging at the VR-1 reactor will help attract students to neutron imaging and might help build future imaging experts.

Overview of MARS: The Multimodal Advanced Radiography Station at the High-Flux Isotope Reactor

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The CG-1D cold-neutron imaging instrument at the High Flux Isotope Reactor at Oak Ridge National Laboratory (ORNL) has been renamed to the Multimodal Advanced Radiography Station (MARS). This reflects upgrades to existing capabilities [1-2] like improvements in sample environment and cameras/optics as well as development of image analysis tools (e.g., [3]) and the neutron grating interferometry technique at ORNL. In this talk, we will present an overview of 1) the current state of MARS, 2) anticipated changes such as possible beamline relocation, and 3) the neutron imaging program in the ORNL 3-source strategy [4].

This research used resources at the High Flux Isotope, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.

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[2] L. Santodonato et al., Physics Procedia 69, 104-108 (2015).

[3] Y. Zhang et al., J. Physics Communications 3(10), 103003 (2019).

[4] https://neutrons.ornl.gov/sts/documents

A New Neutron Imaging Facility at the TRIGA Mark II Reactor of the TU Wien

Burkhard Schillinger presenting for Clemens Trunner

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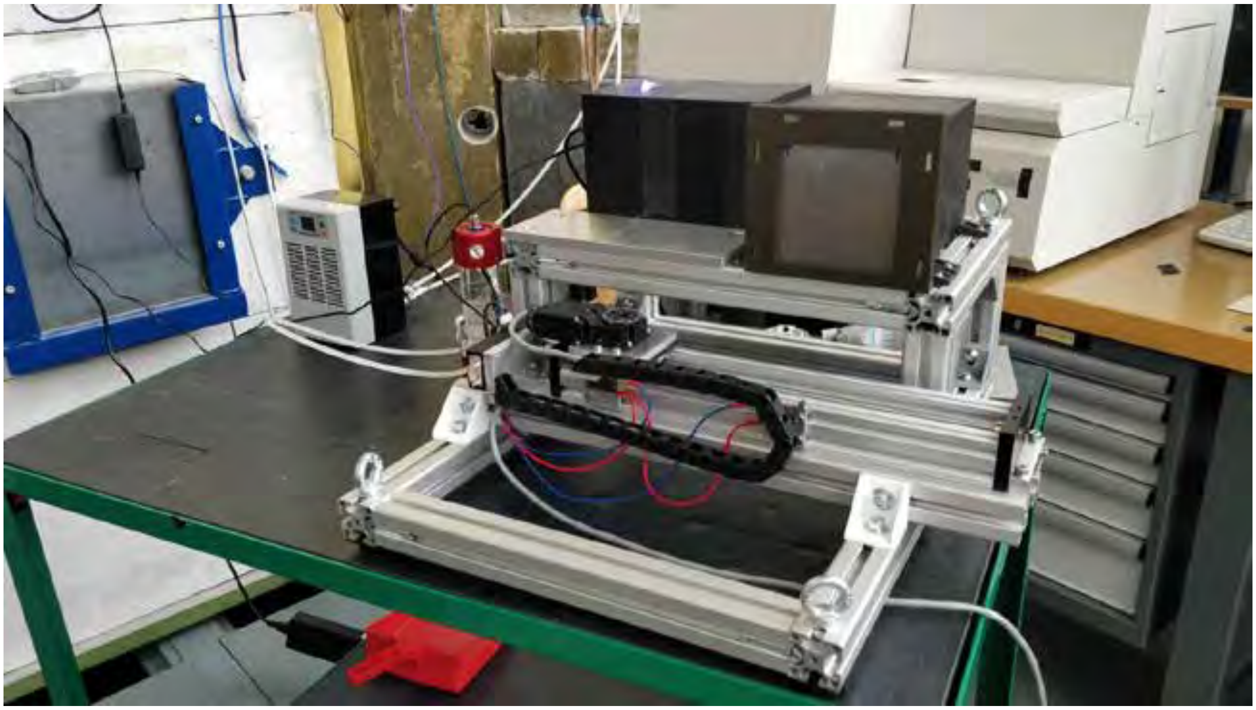
As part of the renewal of some experiments around the reactor, the previous neutron radiography system based on a liquid nitrogen cooled CCD-camera was replaced. Therefore, a new, modern unit was created. During the designing and successive construction of the new radiography station, special attention was paid to the function of the TU Wien as a research facility. Instead of purchasing a commercial system, a special design was created based on plans from the Technical University of Munich, where a similar system is already in use. The new neutron radiography station is a cost-effective instrument that fully corresponds to the state of art technology. This was achieved by using a 3D printer to manufactur most of the parts in-house. The built-in CMOS astro camera with peltier cooling is also a significant improvement over the former system. With the self-developed measuring software and the specifically build controller, a complete and powerful facility was created. By that, a modern instrument for teaching and research is on hand at the TU Wien to perform radiography and tomography with neutrons.



MeV Neutron Imaging at the 60R Beamline at LANSCE

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Neutron radiography with cold and thermal neutrons are established tools established shortly after the first reactors were built. Pulsed spallation neutron sources also enable epithermal neutron radiography, typically utilizing neutron absorption resonances as an additional contrast modality. Neutrons with even higher energies, such as fission, fusion or unmoderated spallation neutrons, offer yet other contrast mechanisms and much deeper penetration into materials. In particular, the attenuation of MeV neutrons by high Z elements, such as tungsten or uranium, is similar to the attenuation by low-Z elements, allowing to e.g. characterize components consisting of light elements inside containers made from high density materials. MeV X-rays on the other hand may be able to penetrate high density materials but have very low sensitivity to components made by light elements inside. The 60R beamline at target 4 at LANSCE provides spallation neutrons produced by ~1ns proton pulses with available neutron energies between 0.1 and 100 MeV at a 1.8 microseconds pulse separation, thus allowing to utilize the time-of-flight for further neutron energy-dependent contrast mechanisms, e.g. absorption resonances of light elements. Limitations of suitable scintillators and detectors inhibited exploitation of MeV neutrons for material characterization in the past. Recently developed nanoguide scintillators and in particular event mode neutron imaging detectors provided substantial advances in making MeV neutron radiography a reality and in this poster we present some results of these efforts. Furthermore, 60R is planned to be upgraded and this poster will provide a brief overview of this effort meant as an invitation to the neutron radiography community to collaborate to improve this unique capability.

The One-Eyed HIPPO: HIPPO Meets ERNI, Upgrading a Neutron Diffractometer with an Energy-Resolved Neutron Imaging Detector

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Neutron diffraction provides information on the crystal structure (nanometer length scale: atom position, crystal symmetry, unit cell dimensions etc.) and micro-structure (micrometer length scale: phase composition, defects/dislocations, texture etc.) of a material. This information is averaged over the entire probed volume of ~1 cm^3. Neutron imaging on the other hand provides information on the spatial distribution of attenuation (sample thickness, concentration of hydrogen or absorbing elements etc.) with a resolution of ~10 micrometers. In case of pulsed neutrons, besides the attenuation, also features such as Bragg-edges (correlated with diffraction peaks) or neutron absorption resonances of specific isotopes can be used to characterize a sample. The HIPPO neutron time-of-flight diffractometer at the short pulse (270 ns base-to-base) neutron spallation source at LANSCE was commissioned in 2001 and since then has conducted hundreds of neutron diffraction experiments, exposing samples to ambient conditions, temperatures above and below ambient, high pressures, applied loads and magnetic fields. Combining such an instrument with an energy-resolved neutron imaging detector provides the entire sample environment suite for imaging experiments and in particular allows to e.g. combine diffraction data with Bragg-edge imaging data for microstructure analysis, observe the decomposition of a hydride at temperature with diffraction and imaging, or measure the sample temperature sensor-less from Doppler-broadened resonances. In January 2024, the HIPPO beamline was upgraded with a LoskoVision TimePix camera to view the nominally 10 mm diameter beam spot. We present the setup and first results of experiments on nuclear fuels, additively manufactured dissimilar welds, steels solidified in microgravity (parabolic flight) as well as hypergravity (centrifugically cast), and minerals and ideally on planned high and low temperature measurements.

Characterization of Event Mode Neutron Imaging Scintillator Detectors

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Event mode neutron imaging detectors using a scintillator screen were successfully built and their usability for neutron imaging was demonstrated recently. Contrary to pixelated images for traditional neutron cameras, the direct output of this detector is a list of the location and time for each recognized neutron interaction. This approach allows the detector to produce data with an unprecedented combination of high spatial and temporal resolution. The processing of individual events allows algorithms such as pulse shape discrimination to be used to suppress the background (e.g. from gammas or detector noise), resulting in high contrast images that can be generated from the output. The event mode output can also be used to extract additional information such as absolute number of neutron counts and event correlations that is not directly accessible when using traditional scintillator based neutron cameras. We present the working principle of this new type of detector as well as measurement results illustrating its characteristics.

WCNR 12

PRESENTATION ABSTRACTS
TUESDAY, 4 JUNE 2024

TUESDAY, 04 JUNE 2024

Pre-session

7:00	Poster Setup (Session B)
8:00	Welcome & Announcements

Material Science | Chair: Pavel Trtik

8:10	**Shieren Sumarli** | Neutron Radiography Techniques for Operando Studies During Laser Powder Bed Fusion
8:30	**Axel Griesche** | Crystallographic Phase Transformations and Corresponding Temperature Distributions During GTAW of Supermartensitic Stainless Steel Visualized by Neutron Bragg Edge Imaging
8:50	**Leslie G. Butler** | Friction Stir Additive Manufacturing: Neutron Interferometry and Bragg Edge Imaging
9:10	**Winfried Kockelmann** Presenting for **Saurabh Kabra** | Stroboscopic Bragg Edge Radiography of Twin Formation in a Magnetic Shape Memory Alloy
9:30	**Anton Tremsin** | Optimization of Liquid-Solid Interface and the Translation Speed for Crystal Growth Through Energy-Resolved Neutron Imaging
9:50	Break

Engineering | Chair: Hassina Bilheux

10:20	**Thawatchart Chulapakorn** | Deformation Structures in Steel Revealed by Neutron Imaging
10:40	**Daisuke Ito** | Measurement of Boiling Two-Phase Flow Pattern Dynamics Using High-Speed Neutron Imaging
11:00	**Takenao Shinohara** | Pulsed Neutron Imaging Study of Energy-Related Devices for Automotive Vehicles
11:20	**Pavel Trtik** | Simultaneous Measurements of Surface Phenomena, Diffusivity and Solubility of Liquids Exposed to High Gas Pressures
11:40	**Frederik Ossler** | Neutron Imaging To Study the Interaction Between Hydrogenous Substances and Porous Carbon Materials and Hydrogen Release in Biomass Pyrolysis
12:00	Poster Pitches - Session B
12:30	Group Photo
12:40	Day 2: Working Lunch: Material Science Application Discussion led by Hassina Bilheux
14:00	Poster Session B
16:00	Break

Facility Upgrades | Chair: Jean Bilheux

16:30	**Alessandro Tengattini |** NeXT 2.0, the Neutron and X-Ray Tomograph at ILL
16:50	**Yuxuan Zhang |** Grating Interferometry Imaging at the High Flux Isotope Reactor
17:10	**Robert Nshimirimana |** Optimization of Neutron Collimator and Shielding for the Refurbishment of the Neutron Imaging Facility at Necsa

Software and Machine Learning | Chair: Jean Bilheux

17:30	**Qianru Zhan |** Enhancing Neutron Tomography for Corrosion Analysis: A Machine Learning Approach for Noise Reduction and Detail Enhancement
17:50	**Mohammad Samin Nur Chowdhury |** Subspace Extraction Algorithm for High-Quality Reconstructions in Hyperspectral Neutron Computed Tomography
18:10	**Shimin Tang |** HyperCT: An Artificial Intelligence Adaptive Hyperspectral Neutron Computing Tomography System
18:10	Adjourn
18:15	**Presentations for WCNR-13 & Board Elections**

Neutron Radiography Techniques for Operando Studies During Laser Powder Bed Fusion

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The worldwide growing interest in metal additive manufacturing, particularly laser powder bed fusion (LPBF), based on the fact that the technique offers fabrications of intricate yet precise geometrical shapes with tailorable physical and mechanical properties. The technique also allows the use of novel feedstock materials, which, when processed with the inherent numerous printing parameters, raises unfamiliar challenges, such as the formation of intermetallic phases. These challenges fuel the urge to develop methods to investigate the influence of the processing parameters and the novel feedstock materials on the evolution of final properties. One set of such methods is performing high-speed operando X-ray diffraction and imaging to observe the LPBF process and reveal the microstructure changes occurring in the process. The limited access of X-rays to the bulk motivates the exploitation of neutrons to non-invasively characterize the process.

Different neutron imaging techniques can be applied to observe temperature [1], density, and phase evolution [2] in operando studies of the LPBF process. To accommodate and benefit from these techniques, a downsized LPBF device for neutron measurements (n-SLM) was developed at the Paul Scherrer Institut (PSI). Operando temperature maps can be produced to observe the temperature evolution with spatial resolution by focusing on the cold wavelength range beyond the last Bragg edge. We also used polarized neutron imaging to map the evolution of ferromagnetic phases, such as martensitic phase transformation, and conventional neutron imaging to identify defects, like evolving porosity and cracks in the printed specimen. LPBF attracts the ability to design and alter microstructures locally according to careful design related to the use of the final part. In order to reliably achieve such designed microstructures with changing processing parameters, geometries, and/or feedstock materials on the fly, understanding the ability to monitor the evolution also under transient conditions is paramount.

The first part of the talk will showcase the technical aspects and potential of the n-SLM machine in the context of operando neutron studies. Subsequently, examples of neutron imaging studies at PSI, Switzerland, as well as the main findings, will be presented.

References:

[1] Biesdorf, J., et al., *Dual Spectrum Neutron Radiography: Identification of Phase Transitions between Frozen and Liquid Water*. Physical Review Letters, 2014. **112**(24): p. 248301.
[2] Busi, M., et al., *Polarization contrast neutron imaging of magnetic crystallographic phases*. Materials Today Advances, 2022. **16**: p. 100302.

Crystallographic Phase Transformations and Corresponding Temperature Distributions During GTAW of Supermartensitic Stainless Steel Visualized by Neutron Bragg Edge Imaging

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We investigated the phase transformations during butt-welding of supermartensitic steel plates with help of Neutron-Bragg-Edge Imaging (NBEI) [1]. Gas tungsten arc welding (GTAW) was used with a motorized torch allowing for automated weldments. The austenitization in the heat affected zone (HAZ) could be clearly visualized at λ = 0.39 nm, a wavelength smaller than the Bragg edge wavelengths of both austenite and martensite. The re-transformation into the martensitic phase during cooling was clearly detected. However, we observed an unexpected additional change in transmission at λ = 0.44 nm, a wavelength larger than the wavelength of the Bragg edges of both the martensitic and austenitic phases. We attribute this change to the Deybe-Waller-Factor that describes the temperature dependence of coherent scattering at a crystal lattice [2]. The observed two-dimensional attenuation map corresponds well with a temperature distribution modelling by software macros in ANSYS [3]. Here, the absolute temperature values could be achieved by calibrating the modelled attenuation with help of a thermocouple placed at the steel plate. This allows in return for a direct two-dimensional temperature reading based on the Debye-Waller-relation between neutron attenuation and sample temperature.

[1] A. Griesche, B. Pfretzschner, U. A. Taparli and N. Kardjilov, Appl. Sci., 11, 10866 (2021).
[2] R.S. Ramadhan, W. Kockelmann, T. Minniti, B. Chen, D. Parfitt, M. E. Fitzpatrick, A. S. Tremsin, J. Appl. Crystallogr. 52, 351–368 (2019).
[3] https://www.ansys.com/

Friction Stir Additive Manufacturing: Neutron Interferometry and Bragg Edge Imaging

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Kyungmin Ham[2], **James Torres**[3], **Anton Tremsin**[4]

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Cross sections of friction stir additive manufacturing (FSAM) are, a priori, expected to show layering. However, conventional X-ray tomography and neutron transmission imaging only weakly show layering. In contrast, neutron interferometry, particularly the modality called dark-field imaging or scattering imaging, shows a rich layered structure. The layering structure is further refined with Bragg edge imaging of the aluminum FSAM test coupons.

Aluminum FSAM is performed in air, uses a graphite lubricant, and due to tool path constraints, has the potential for hot-on-hot and hot-on-cold structuring. A sample series was developed explore these potential causes for a layered structure and correlate observed structure with mechanical test properties, all with a build layer increment of 1 mm. Linear FSAM test coupons were sliced into 20 mm thick sections along the tool path, subjected to three-point loading, polished, and imaged with X-ray tomography and neutron radiography. Sections were also studied with backscattered electron imaging and electron backscatter diffraction imaging.

The Multimodal Advanced Radiography Station at Oak Ridge National Laboratory, High-Flux Isotope Reactor, CG-1D, was used for neutron interferometry for autocorrelation lengths of 30 to 800 nm. The J-PARC NOBORU beamline was used for Bragg edge imaging from 1 to 5 Å. Preliminary analysis shows that both Bragg images and dark-field interferometry images reveal layering structures that are correlated with the 1 mm build layer, tool path direction, lubrication, and post-print processing.

Data fusion is in process. Intermediate goals are merging the neutron imaging data with the BSE and EBSD images as well as neutron-guided enhancement of the X-ray tomography data, the only 3D data acquired in this project.

Stroboscopic Bragg Edge Radiography of Twin Formation in A Magnetic Shape Memory Alloy

Winfried Kockelmann presenting for Saurabh Kabra

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Bragg edge imaging is typically time-consuming, taking minutes or hours for radiography and many hours for tomography. Stroboscopic neutron imaging provides an opportunity to capture fast and repetitive processes with a comparatively slow technique such as Bragg edge analysis. Previously, an asynchronous stroboscopic data collection scheme was proposed for recording repetitive motions at a pulsed neutron source [1]. We have implemented stroboscopic Bragg edge analysis on a time-of-flight (TOF) neutron imaging instrument for recording dynamic microstructure changes in a magnetic shape memory alloy.

Magnetic shape memory alloys are a class of materials which produce large elongations of several percent upon application of a magnetic field. This property combined with their fast response makes them ideal for actuator applications. Ni_2MnGa exhibits such a magnetic shape memory effect at ambient temperatures through a twinning deformation mechanism. We have performed stroboscopic Bragg dip radiography on Ni_2MnGa single crystals using a custom-made magnetic field generator which produced specific discharge current waveforms. The stroboscopic measurements were performed on IMAT on the 10 Hz pulsed source at the ISIS second target station in a neutron wavelength range between 1 and 6.5 Å. Bragg dip spectra were collected with a microchannel plate (MCP) detector in an event list mode, achieving a spatial resolution of about 200 μm and a time resolution of the sample processes of a few milliseconds.

The stroboscopic asynchronous imaging method, used here for studying twin formation, is essentially a radiographic 4D technique (x-y pixels, TOF, magnetic field phase) using a medium-flux neutron source. The technique can potentially be expanded to tomography and employed for neutron imaging of other cyclic processes, to achieve time-lapse and in-situ energy-resolved imaging of fast dynamic processes.

[1] B. Schillinger, Journal of Neutron Research, 16 (2008) 121-126.

Optimization of Liquid-Solid Interface and the Translation Speed for Crystal Growth Through Energy-Resolved Neutron Imaging

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Availability of newly discovered scintillator and semiconductor materials is often hindered by the slow process of crystal growth optimization needed for obtaining sample sizes matching the attenuation length for the radiation to be detected. The dimensions of these materials used in detection devices are typically in a several cm-scale range or larger, which means crystals need to be grown into large dimensions. It is a very difficult process for many advanced materials involving multiple chemical elements. Optimization of crystal growth parameters is often performed by a trial-and-error methods due to opacity of many materials to conventional nondestructive probes (e.g. X-rays, e-beams, optical lasers). Energy-resolved neutron imaging appeared to provide unique information on the crystal growth conditions and allows monitoring in-situ various growth parameters such as elemental distribution within the solid material and the melt, the location and the shape of liquid-solid interface, mosaicity of solidified material, segregation and diffusion of dopant elements during growth, the presence of defects and others. Among the parameters which need to be optimized during crystal growth are the shape of the interface between liquid and solid phases and the speed to translation, which determines the time required to grow the crystal. In this talk we present our study on how these two important parameters can be optimized in-situ with the help of energy-resolved neutron imaging. We visualize how the variation of temperature profiles in the Bridgeman furnace can lead to the inversion of the liquid-solid interface. At the same time, variation of translation speed beyond sustainable heat extraction leads to instabilities in the liquid-solid interface and results in a very non-uniform elemental composition of the grown material, as shown in Figure 1. We will present in-situ crystal growth optimization for multiple advanced gamma and neutron detection materials and discuss the future possibilities of this non-destructive technique in the application of crystal growth as well as metal allowing.

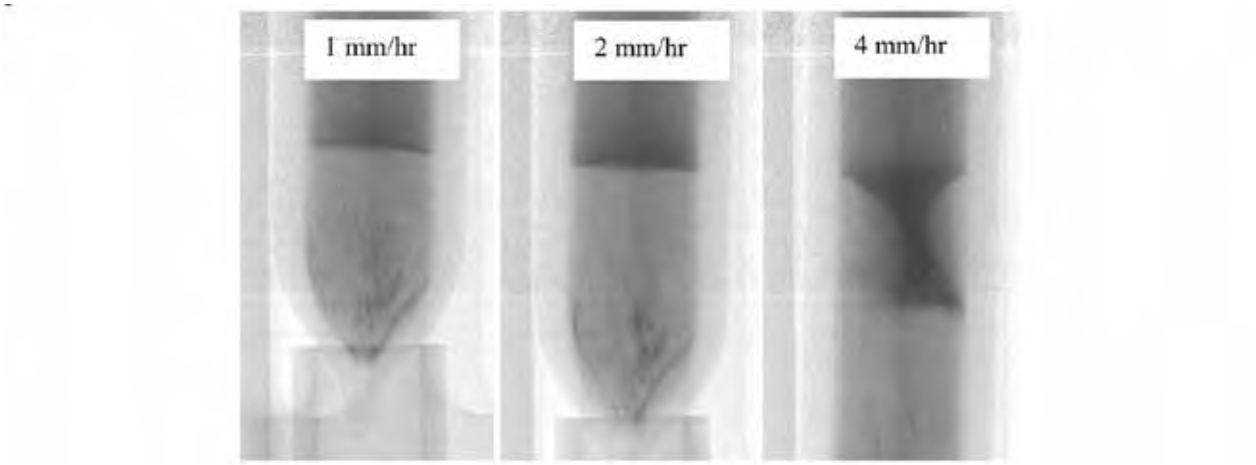

Figure 1. Location and the shape of liquid-solid interface in CsI:0.5%Eu visualized with the help of energy resolved neutron imaging.

Deformation Structures in Steel Revealed by Neutron Imaging

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ARMCO® is a technically pure iron and, because of its unique properties, still widely used in modern applications such as electromagnetic components. The magnetic properties are highly influenced by the amount of mechanical deformation (e.g. grain size and the internal stress). We studied tensile samples made from ARMCO® at different amounts of applied stress. As-received tensile samples made from 4-mm-thick sheet metal exhibited an average grain size of 70 µm and a low number of crystal defects. The neutron transmission through these samples has been found to be significantly higher than the one obtained from a fine grain iron powder for the same thickness. Upon applying even small amounts of plastic deformation (elastic limit of the macroscopic yield point), we observed a drastic decrease of the neutron transmission. Using wavelength selective imaging, we observed that this difference originates from the elastic coherent cross section (prior to reaching the Bragg cut-off). Although the average grain sizes all over the sample remained at ~70 µm, Transmission Electron Microscopy (TEM) showed an increase of so-called sub-grains within individual grains in the regions that experienced higher stress, which was also monitored by surface based Digital Image Correlation (see Figure 1). These results suggested a high sensitivity to deformation structures, and we also were able to correlate neutron transmission with neutron diffraction intensities. The observed differences can hence be attributed to primary (diffraction) extinction [1] and multiple scattering.

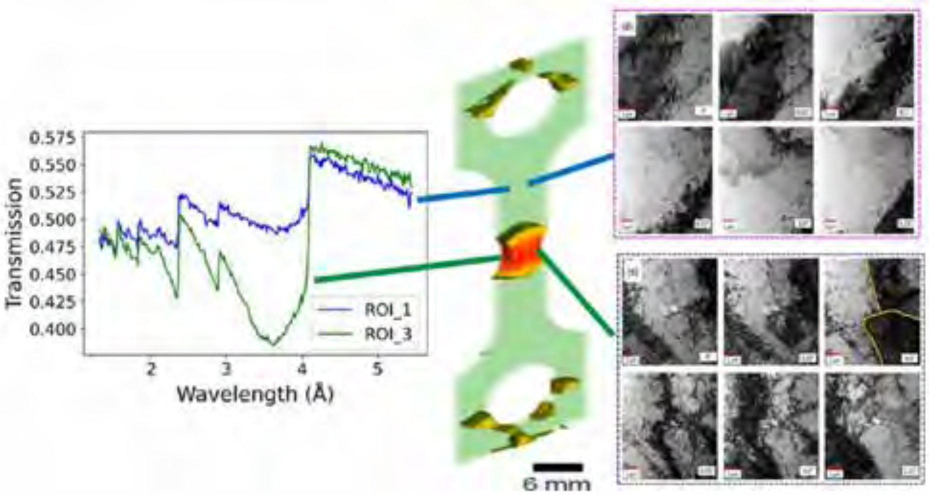

Figure 1. *Ex-situ* neutron tomography on an iron sample subjected to 160 MPa load is shown (in the middle), where a lower transmission in deformed region was noticed. ToF transmission in different contrast zones, referring to different micro-strain, are revealed on the left panel together with the microstructure in the corresponding regions on the right panel.

[1] H. Sato *et al*., J. Imaging, 4 (2018) 1-25.

Measurement of Boiling Two-Phase Flow Pattern Dynamics Using High-Speed Neutron Imaging

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In boiling water reactors, the cooling water boils within the reactor core. Transitions in two-phase flow patterns, such as bubbly flow, slug flow, and annular flow, occur along the direction of the flow. In conventional reactor thermal-hydraulics analysis, different parameters and constitutive equations are used for classified flow patterns. Therefore, accurately identifying the flow pattern in the channel is crucial for highly precise predictions. This study aims to investigate changes in the flow pattern of boiling two-phase flow in a heated pipe using neutron imaging and to clarify its dynamics by analyzing temporal fluctuations. Neutron imaging proves effective in understanding thermal-hydraulic phenomena in metallic pipes due to its high transmissivity and has been applied in various applications. While most previous studies have focused on average characteristics, measuring spatio-temporal characteristics can provide new insights by using a high-speed imaging system.

Experiments were conducted in the B-4 facility of KUR. A high-speed imaging system comprising an optical image intensifier and a high-speed camera was employed to capture sequences of neutron transmission images of boiling flow at 1000 fps. The test section featured a stainless-steel tube with an inner diameter of 10 mm, heated by Joule heating. The cross-sectional average void fraction was calculated from the instantaneous void fraction distribution estimated from the transmission images. The dynamics of the flow pattern in the tube were analyzed based on its spatio-temporal distribution. An example of the spatio-temporal distribution is shown in Fig. 1. In the middle of the heated section, bubble generation begins, and the rise of bubbles is observable in the distribution. In the upper part of the tube, the flow changes to the annular flow, and the movement of the liquid film appears as stripes. Thus, understanding the dynamic characteristics of the flow structure and identifying the pattern can be achieved by estimating characteristic quantities from it.

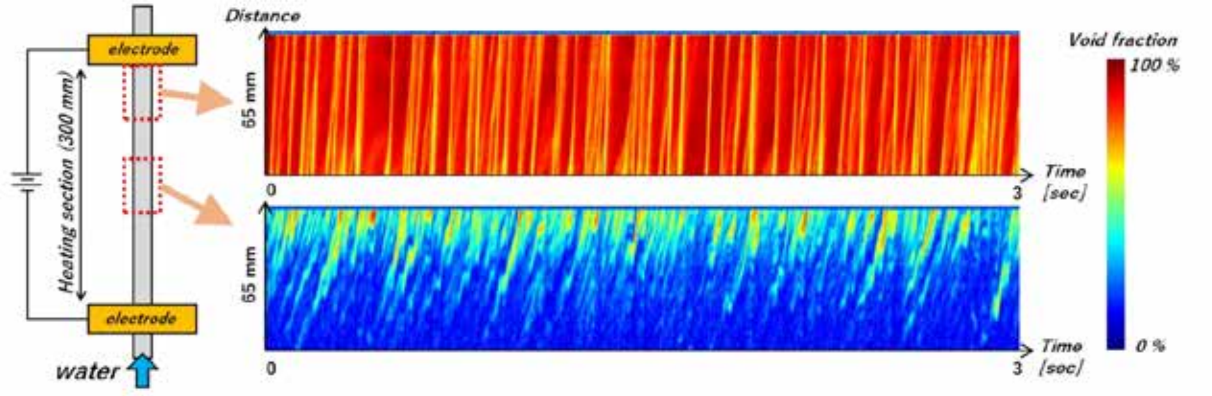

Figure 1. Spatio-temporal distributions of void fraction in a heated tube (q = 290 kW/m^2, G = 200 kg/s, ΔT_{sub} = 20 K).

Pulsed Neutron Imaging Study of Energy-Related Devices for Automotive Vehicles

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Reducing greenhouse gas emissions and achieving carbon neutrality are pressing issues to mitigate the global climate change. The energy-related devices such as fuel cells and Li ion batteries are considered as the key technologies for this problem and have been vigorously investigated to improve their performance. Neutron imaging has attracted strong interests in the study of these devices because it is available to visualize the water distribution inside the cells or the behavior of Li atoms inside the batteries during their operation.

At RADEN in J-PARC, projects have been carried out to study these devices, which are specifically targeted for automotive vehicle use. In-operando imaging of the practical fuel cell, which is actually installed in the TOYOTA's Fuel Cell Electric Vehicle (FCEV) "MIRAI", has been conducted, and recently we have succeeded in performing water/ice discrimination using this practical full-size fuel cell by means of the neutron energy selective imaging by Time-of-Flight gating of the pulsed neutrons and observing water behavior under simulated cold-start conditions at sub-zero temperatures [1]. In addition, we also conducted in-situ observation of internal phenomena of a commercial Li-ion battery during heating up to thermal runaway by developing a special protection chamber [2]. As a result, the liquid electrolyte fluctuation inside a battery and the deformation of the protective plastic film during heating were clearly observed.

In this presentation, we will present recent activities at RADEN, and discuss the results of pulsed neutron imaging experiments on the energy-related devices. This work was partially conducted under the NEDO organization project, JPNP20003.

[1] Y. Higuchi et al., Commun. Eng. (accepted).
[2] H. Nozaki et al., Sci. Rep. 13, 22082 (2023).

Simultaneous Measurements of Surface Phenomena, Diffusivity and Solubility of Liquids Exposed to High Gas Pressures

Pavel Trtik presenting for Vopič ka Ondrej

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Neutron imaging allows for the simultaneous measurement of surface phenomena, diffusivity and solubility for liquids exposed to highly pressurized gas in optically opaque vessels. The feasibility of this 'one-pot' type measurements was first demonstrated on an example of absorption of methane (up to 120 bar gas pressure) into perdeuterated ethanol (methane hydrate freeze-out inhibitor) and perdeuterated n decane (model compound of crude oil) under ambient temperature [1]. The follow-up investigations focused on the investigations enabled to reveal and quantify multiple phenomena occurring in supercooled liquid p xylene solutions of methane under pressures relevant to the freeze-out formation in the production of liquefied natural gas [2].

After a short overview of these initial results, the constraints determining the sensitivity and uncertainty of the methodology will be discussed. Likewise, the results showing the applicability of the same approach to the measurement of the interfacial tensions of two liquids will be presented and prospects regarding measurements of the surface properties of inorganic liquids will be given.

The presented experimental data also serve as calibration sets for the initial molecular dynamics simulations. This will allow future in-silico assessment of these gas-liquid systems under hardly experimentally achievable conditions.

Acknowledgement

OV, T-MD, JH, MM, and PT acknowledge the financial support obtained from Czech Science Foundation (GACR) and Swiss National Science Foundation (SNSF) within the research project 23-04741K. MM, ST, JS acknowledge the support obtained from The Ministry of Education, Youth and Sports within the specific university research grant A1_FCHI_2024_001.

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[2] Vopička, et al., 10.1038/s41598-022-27142-6

Neutron Imaging to Study the Interaction Between Hydrogenous Substances and Porous Carbon Materials and Hydrogen Release in Biomass Pyrolysis

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The work shows a summary of research results from collaborative work between people (researchers/engineers/technicians) from Lund University and the Oak Ridge National Laboratory, Oak Ridge (TN). The Neutron imaging experiments were performed at the High-Flux Isotope Reactor (HFIR), beamline CG-1D. Studies included porous carbons' interactions with methane, ethane and propane at various pressures from low pressure up to 100 bar and from cryogenic- to room temperature [1,2]. The goals of the studies are to reach a better understanding of sorption and phase transitions inside and outside the porous medium at varying pressure and temperatures and to obtain quantitative evaluation of the amount of hydrogenous substances at the different stages of phase transition and sorption. The Porous carbons studied include materials such as activated chars and carbon/flame soot-based materials.

In addition, experimental studies on H-release dynamics were performed using operando neutron radiography on biomass pyrolysis up to 1000°C [3]. Defining a method based on the neutron attenuation ratio over the samples we were then able to evaluate their amount of H and their relative changes of H during the thermochemical conversion process. It was also possible to compare the results from the pre- and post-pyrolysis neutron computer tomography data. Results from the studies have been useful for modelling of biomass pyrolysis [4].

Recently, starting from the pandemic period, we have performed combined neutron- and X-ray micro-tomography studies on pyrolysis. The measurements were performed at the Institut Laue Langevin (ILL) NeXT beamline in Grenoble to measure local variations of H-to-C- and H- to-(C+O) ratios in in biomass that have undergone different levels of pyrolysis/burning. This helps us to better understand how properties such as pore and capillary structure [5,6] may influence the chemical and physical processes in thermochemical conversion for different biomass derived materials.

The presentation will discuss some different aspects resulting from the investigations.

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[1] F. Ossler, L. J. Santodonato, H. Z. Bilheux In-situ neutron imaging of hydrogenous fuels in combustion generated porous carbons under dynamic and steady state pressure conditions, Carbon 116 (2017) 766-776;
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NeXT 2.0, The Neutron and X-Ray Tomograph at ILL

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NeXT-Grenoble is the Neutron and x-ray tomograph born in 2015 from a collaboration between the Institut Laue-Langevin (ILL) and University Grenoble Alpes (UGA). This instrument has undergone a complete overhaul to further expand the portfolio of contrast options. This is the result of a collaboration between the initial partners (UGA and ILL) plus the Helmholtz-Zentrum Berlin (HZB), also via the newly founded international mixed research unit NI-Matters. This upgrade adds MoTo, a Monochromatic Tomograph tailored for advanced techniques such as grating interferometry and polarized neutron imaging.

The upgrade has improved the highest attainable spatio-temporal resolutions by increasing the maximum flux (expanding the accessible collimation ratios L/D) as well as by upgrading the range of detectors. The simultaneous x-ray imaging has also been improved to explore a broader range of geometrical configurations. An improved sample stack helps automate and expands the possibilities (in size/weight) of in-situ apparatus that can be easily installed on the instrument, as well as adding a laminography option.

The installation of a velocity selector as well as a double crystal monochromator provides versatile energy selection, opening up for additional contrast mechanisms. A grating interferometer allows the characterization of heterogeneities on the scale of 0.1 μm to 10 μm and above through dark-field imaging, while differential phase contrast can be employed to differentiate even modest variations in the refractive index. The new instrument also has a native integration of neutron polarization equipment in order to perform vectorial tomographies of magnetic fields.

This presentation will provide an overview of the science made at NeXT in the last years, detail the upgrade of NeXT and of MoTo and highlight new scientific venues that are being explored thanks to these new options.

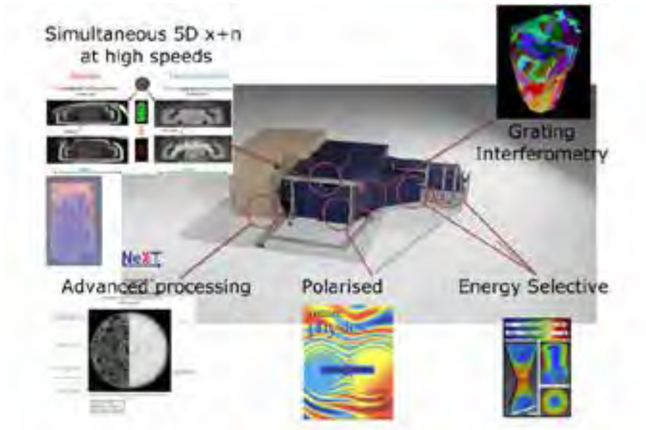

Figure 1. A schematic representation of the upgraded instrument.

Grating Interferometry Imaging at the High Flux Isotope Reactor

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Neutron imaging is a non-destructive probe that can investigate bulk materials' internal features/structures. Neutron grating interferometry (nGI), an advanced neutron imaging technique, enables simultaneous access to three contrast mechanisms: attenuation, differential phase, and small angle neutron scattering. In collaboration with Louisiana State University, a Talbot-Lau grating interferometer was implemented at the Multimodal Advanced Radiography Station (MARS) at the High Flux Isotope Reactor (HFIR) early 2021. Since then, efforts have been focused on improving nGI performance in terms of visibility, operational effectiveness, and access to a broader range of auto-correlation lengths. In this work, recent progress will be presented and discussed.

Acknowledgments

This research used resources at the High Flux Isotope Reactor, U.S. Department of Energy (DOE) Office of Science User Facility operated by the Oak Ridge National Laboratory.

Optimization of Neutron Collimator and Shielding for The Refurbishment of the Neutron Imaging Facility at Necsa

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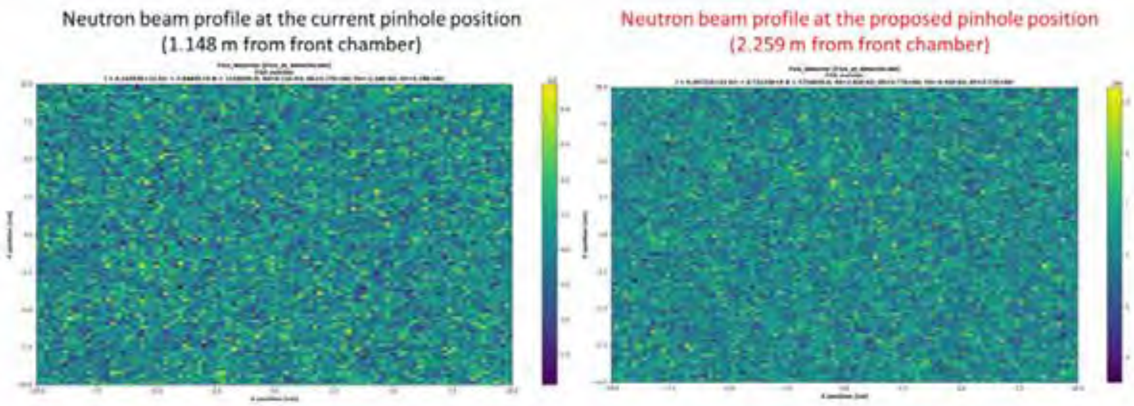
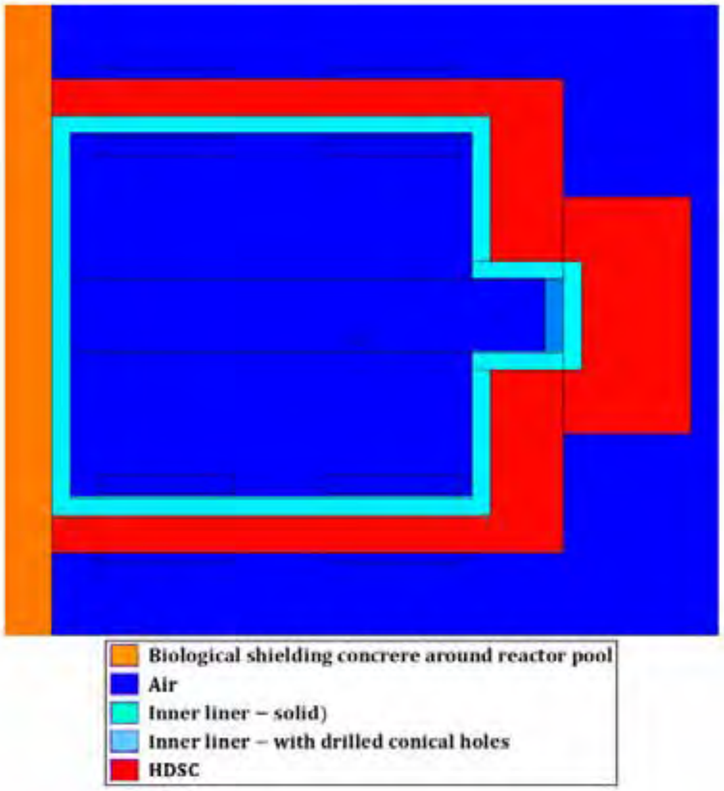
Neutron imaging facilities have evolved into multidisciplinary research laboratories, finding applications in non-destructive testing, cultural heritage, agriculture, energy sector, civil engineering, bio-sciences, metallurgy, geo-sciences, etc. To beneficiate this versatility, the South African Nuclear Energy Corporation (NECSA) is re-establishing neutron imaging capabilities at the SAFARI-1 research reactor by refurbishing the existing facility. The refurbishment project involves optimizing the geometry and position of the collimator to enhance the neutron beam quality, homogeneity and resolution. In addition to this, the facility shielding and the beam catcher are being optimized to minimize the floor loading weight as well as beam scattering within the experimental chamber. The refurbished collimator and primary shutter will incorporate modern and proven shielding materials. For the facility shielding two high-density compositions are being considered: High-density concrete containing high-grade hematite with added steel granules; slurry mixture comprising steel granules, ferroboron, and liquid paraffin. To further minimize scattering in the experimental chamber, an optimized thickness of an inner liner made of 5% borated polyethylene will cover the shielding walls and the beam catcher. This presentation discusses the results of the collimator optimization and the shielding optimization of the two shielding mixtures using both ray-tracing and Monte Carlo modelling respectively with McStas and MCNP.


Neutron beam profile at the current pinhole position
(1.148 m from front chamber)
Neutron beam profile at the proposed pinhole position
(2.259 m from front chamber)


🟧 Biological shielding concrere around reactor pool
🟦 Air
🟦 Inner liner – solid)
🟦 Inner liner – with drilled conical holes
🟥 HDSC

Enhancing Neutron Tomography for Corrosion Analysis: A Machine Learning Approach for Noise Reduction and Detail Enhancement

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Neutron tomography, as a distinctive non-destructive technique, plays a vital part in revealing fine details and subtle changes in complex samples, including reinforced concrete or cultural heritage artifacts. While most efforts in the field of computed tomography (CT) have been dedicated to sophisticated reconstruction algorithms particularly for low-dose CT[1-3], our research redirects focus towards denoising in neutron tomography. Despite of adherence to the sampling theorem critical to capturing the fine details essential for corrosion sample analysis, challenges remain in neutron tomography. The inherently low signal-to-noise ratio (SNR) in neutron imaging, malfunctions from the detector, and the natural low-contrast features within the samples complicate the analysis and hinder further material science investigations. Hence, robust denoising techniques are indispensable. However, traditional methods offer limited success[4], constrained by high computational demands, extensive hyper-parameter tuning, and the potential introduction of bias and artifacts.

This study proposes to adapt the LIDIA model (Lightweight Learned Image Denoising with Instance Adaptation)[5], a novel machine learning approach inspired by the BM3D (Block Matching and 3D Filtering)[6] denoising algorithm, to address the specific challenges in neutron tomography. Building upon our previous research that enhanced contrast-to-noise ratio (CNR) using traditional denoising methods[7], this research aims to harness LIDIA's combination of BM3D's robustness and the adaptability of neural networks. Our focus is to optimize LIDIA for the unique noise characteristics and detail preservation requirements in neutron tomography, specifically for corrosion sample analysis. By integrating an ML-based approach into neutron tomography, we aim to set new standards in image quality and advance in non-destructive testing and analysis, enhancing the capability of neutron imaging in detecting and characterizing corrosion.

Keywords: Neutron Tomography, Machine Learning, LIDIA Network, Image Denoising, BM3D, Nondestructive Testing.

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Subspace Extraction Algorithm for High-Quality Reconstructions in Hyperspectral Neutron Computed Tomography

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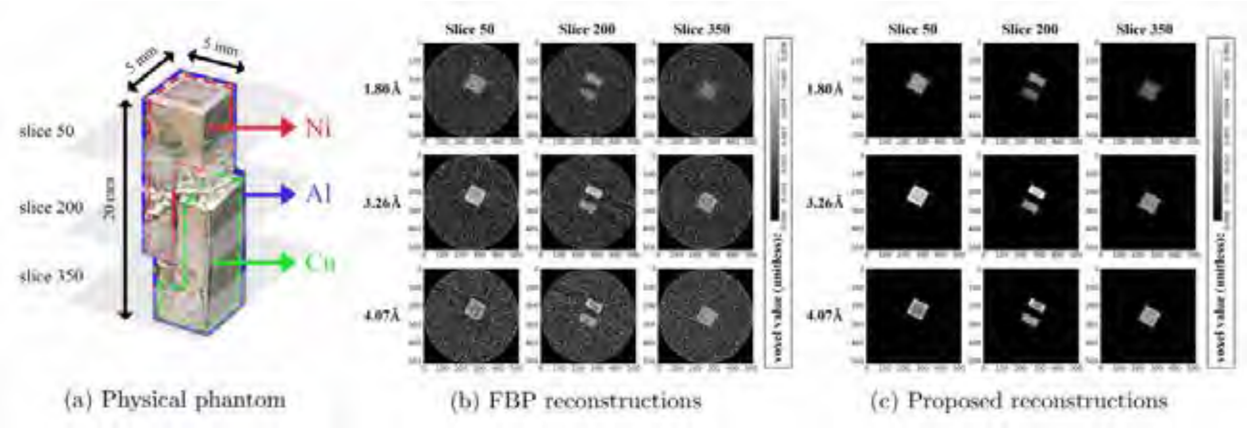
Hyperspectral neutron computed tomography (CT) enables 3D non-destructive imaging of the spectral characteristics of materials. A typical measurement involves recording the transmission data (radiograph) resulting from the interaction of pulsed neutrons with the sample of interest and resolving it into thousands of spectral bins using the time-of-flight information. This process is repeated by rotating the sample, and the resulting data is typically reconstructed one spectral bin at a time. The reconstruction procedure is computationally expensive, even with a simple algorithm like filtered back projection (FBP). Furthermore, the resulting reconstructions may have a significant amount of noise as the radiographs for the individual spectral bins have low signal-to-noise ratios (SNR), and the number of orientations is small due to the limited availability of beam time.

In this work, we propose an algorithm that dramatically suppresses noise while being computationally efficient. It involves the following steps:

1. Dimensionality Reduction: Perform a subspace extraction procedure where the hyperspectral measurements are decomposed into intermediate dimensional subspace basis vectors and corresponding subspace projections using non-negative matrix factorization (NMF).
2. Subspace CT Reconstruction: Reconstruct the subspace projections using a model-based iterative reconstruction (MBIR) algorithm with automated parameter selection that enables high-fidelity reconstructions from sparse and low SNR datasets.
3. Full Hyperspectral CT Reconstruction: Compute the hyperspectral reconstructions of interest using the subspace reconstructions and the subspace basis vectors.

The number of subspace components is much smaller than the number of spectral bins, making it possible to apply sophisticated reconstruction algorithms like MBIR within a reasonable time. Furthermore, the dimensionality reduction step helps suppress noise, as the residual difference from NMF mainly accounts for the data noise. We evaluated our algorithm on data from the sample shown in Fig. 1 (a), measured using the Spallation Neutron Source at Oak Ridge National Laboratory, USA. The dataset contains hyperspectral measurements from 27 projection angles, comprising 512 × 512 radiographs at 1200 wavelength bins for each projection angle. However, we excluded the top and bottom 50 slices during reconstruction. We compared our results to the FBP approach that is commonly used for CT scans at reactors. Fig. 1 (b) and (c) show slices from the hyperspectral reconstructions at specific wavelengths estimated using FBP and our method (using 9 subspace components), respectively. Our algorithm produces hyperspectral reconstructions with significantly less noise compared to FBP. The FBP method, when applied to each channel sequentially, required about 634.06 minutes, while the proposed method only required about 60.31 minutes on a 64-core compute node – an order of magnitude reduction in run-time. (a) Physical phantom (b) FBP reconstructions (c) Proposed reconstructions



(a) Physical phantom (b) FBP reconstructions (c) Proposed reconstructions

Figure 1: Hyperspectral reconstructions of the Ni-Cu-Al sample: (a) physical phantom, (b) FBP reconstructions, and (c) proposed reconstructions.

G. Buzzard was partially supported by NSF CCF-1763896, and C. Bouman was partially supported by the Showalter Trust. This research used resources at the Spallation Neutron Source, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.

HyperCT: An Artificial Intelligence Adaptive Hyperspectral Neutron Computing Tomography System

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Hyperspectral neutron computed tomography (HSnCT) is a cutting-edge imaging capability which utilizes wavelength dependent information to differentiate materials and phases. Bragg edge and resonance imaging are the major techniques to be deployed at VENUS, as these techniques provide unique contrast mechanisms based on crystalline properties and elemental/isotopic content, respectively. Compared to white-beam neutron CT performed at the reactor source, HSnCT acquires acquires radiographs corresponding to a wide range of wavelengths, resulting in much longer acquisition time for sufficient SNR across each of these wavelengths. Therefore, the traditional experimental workflow which consists of reconstructing the object using the filteredback-projection (FBP) reconstruction faces various challenges. For example, the long measurement time increases data costs, which requires every projection needs to provide maximum information about the sample. In essence, each monochromatic radiograph suffers low signal-to-noise ratio, and the overall CT scan has sparse hyperspectral projection data due to the constrained beam time, which will render FBP unsuccessful.

In response to these challenges, we developed HyperCT (shown in Figure 1), an innovative artificial intelligence (AI) approach designed for the following capabilities:

1. Autonomous projection acquisition based on the assessment of previous hyperspectral reconstructions, which adapts to the geometry of each sample to be scanned.
2. Advanced model-based iterative reconstruction (with the ability to upgrade using deeplearning methods) to perform high quality reconstructions with sparse projections.
3. Autonomous decision-making to conclude a scan and move to the next sample using a comprehensive reconstruction quality metric, based on a 3D Convolutional Neural Network.

4. Real-time monitoring mechanism to guarantee all projections are measured correctly.

Furthermore, HyperCT is a versatile modular system accommodating diverse neutron imaging samples. For instance, its deep-learning-based reconstruction module enhances efficiency when scanning multiple similar samples within a limited time. Additionally, the quality metric is adjustable, catering to the unique characteristics of individual samples. This adaptive nature positions HyperCT as a robust solution for advancing HSnCT capabilities in neutron imaging research and is extendable to X-ray imaging at synchrotron facilities.

We will present HyperCT in a poster while the presentation will focus on the deep-learning-based MBIR method.

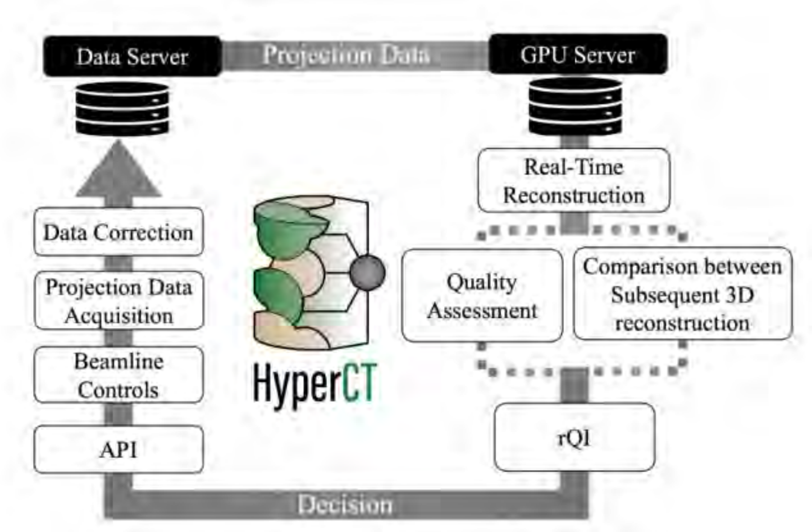

Figure 1. Overall workflow of our streaming HyperCT capability showing the machine learning component of the autonomous loop.

This research used resources at the Spallation Neutron Source, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory. This research was supported in part by the Shull Wollan Center at the University of Tennessee and the National Science Foundation through Award CBET-1454437.

WCNR 12

POSTER ABSTRACTS
TUESDAY, 4 JUNE 2024

Evaluation of Operating Characteristics of Oscillating Heat Pipe Based on Flow Visualization by Neutron Radiography

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Hiroshi Iikura[2], Hitoshi Asano[1]
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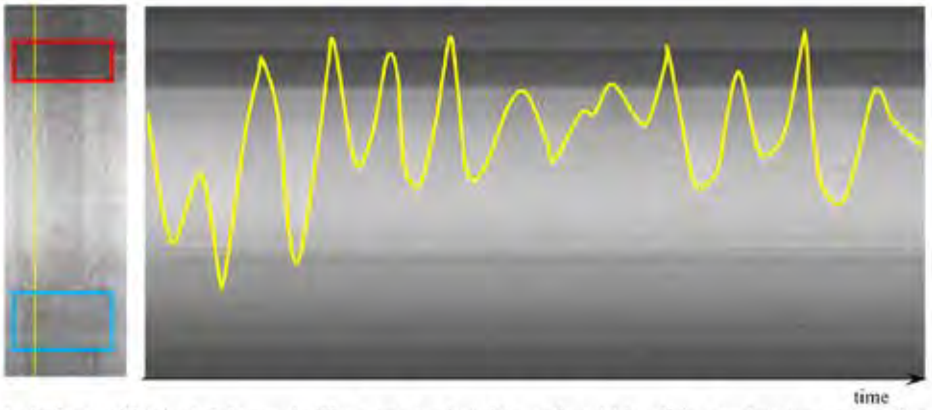
High-performance heat spreaders are required for high heat flux cooling of high-power electrical equipment. Oscillating heat pipes (OHPs) is expected to be passively operated heat transport devices without mechanically driven components. OHPs consist of meandering small diameter channels, where heat is transported by the movement of refrigerant liquid plugs formed in the channels. In order to design OHPs, it is necessary to clarify the interaction between the oscillatory motion of the liquid plug and the heat transfer performance, in particular the effect of the alignment against gravity. In this study, liquid plug behaviors in an aluminum OHP were visualized by a neutron radiography using the facility in the research reactor JRR-3 of Japan Atomic Energy Agency. The OHP was manufactured from a flat multi-port tube with 42 parallel channels, which were connected to form a single meandering channel. The cross-sectional shape of the channels was square with 0.8 mm per side. Radiographs on a scintillator were captured by a high frame-rate camera with the frame rate of 500 fps and exposure time of 2 ms. The pixel size of the captured image was 280 μm. The left figure shows an original radiograph. A time-strip image processing technique was applied to measure the amplitude and frequency of the liquid plug oscillation. Factors contributing to the poor heat transfer performance in top-heat mode operation were identified from the flow visualization.



Left figure: Original radiograph. The areas enclosed by red and blue lines are heating and cooling sections, respectively.
Right figure: Time-strip image for a channel indicated by a yellow line in the left figure. The curve shows the movement of the gas-liquid interface.

iBeatles: Bragg Edge Imaging Software for the VENUS Beamline at the Spallation Neutron Source

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VENUS is currently being built at the Oak Ridge National Laboratory and will enter its commissioning phase this summer. Because neutron wavelength dependent imaging is a relative recent technique, software needs to be developed to reduce and analyze these data. We implemented the python-based application iBeatles (Imaging Bragg Edge Analysis TooLs for Engineering Structures). At the 11th NEUtron WAVElength dependent workshop (NEUWAVE-11), the community provided important feedback to improve iBeatles. Several of these suggestions have been incorporated into iBeatles since NEUWAVE-11. Our poster presents the new interface and highlights the new improvements. Some of the new features are the possibility to combine various data sets or to rebin time-of-flight(TOF) data.

Figure caption. Screenshots of the iBeatles General User Interface.

A portion of this research used resources at the Spallation Neutron Source, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.

High Light Yield Plastic Scintillator Screens for Neutron Imaging

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For MeV neutron radiography and computed tomography, we have fabricated both contiguous and segmented plates of a high light yield plastic scintillator that offers light yields 3x higher than standard plastic, and comparable to that of ZnS(Cu). This plastic employs an iridium complex fluorophore to produce a high light yield, centered in the green near 540 nm, near the peak quantum efficiency of amorphous silicon panels and CCD cameras in order to optimize readout. A bright, transparent scintillator provides new options to increase imaging throughput in neutron imaging, several examples will be described.

Monte-Carlo Simulation of Prompt-Gamma Ghost Imaging

Cheng-i Chiang[1], Cheng-i Chiang[1], Alaleh Aminzadeh[1], Wilfred Fullagar[1], Ulf Garbe[2], Filomena Salvemini[2], Joseph Bevitt[2], David Paganin[3], Andrew Kingston[1]

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Neutron Activation Analysis (NAA) can determine elemental concentrations in a sample. It relies on measurement of gamma rays emitted from a sample after neutron irradiation. The emitted gamma spectra are based on the neutron-nucleus interaction. The measured spectrum can identify the atomic composition of the target object. The gamma rays produced can be divided into two categories, namely "prompt gamma" rays emitted almost instantaneously after neutron interaction with a nucleus, and "delayed gamma" rays emitted from nuclei after a longer time scale. We explore the possibility of using ghost imaging (GI) to add spatial information to prompt-gamma (PG) NAA. Ghost imaging is a novel computational imaging method that does not require one to directly measure the sample with a pixelated detector. Instead, the object is illuminated with a set of patterns and the total interaction (gamma emission in this case) is recorded with a single-sensor, or bucket detector. An image of the object is determined based on the correlation between the patterns and bucket measurements. The overall goal of the project is to explore the combination of these two methods, namely NAA and GI, to measure the spatial distribution of elements in a sample.

A first step to realising prompt-gamma ghost imaging (PG-GI) is to simulate it with a particle-physics simulation tool. This can demonstrate the principle and allow us to better understand the appropriate experimental scenarios and acquisition times to successfully realise PG-GI experimentally. The results of our simulations to date are reported here. We used the TOPAS Monte-Carlo particle simulation tool (topas-mc.org) to simulate the physical interaction process; this software is based on Geant4. We modelled the "Dingo" neutron imaging beamline environment, including the neutron source, collimator, and detector with an additional gamma-ray sensor. We then set up a GI experiment using a random Cd mask to visualise the distribution of gold in a simple object, as a demonstration of the principle. Our results are encouraging as they show that we are simulating the physics reasonably well. However, they also show that sample choice is important, and that work is required to refine the experiment design. To further refine the model and improve on these initial results we plan to incorporate a more physically realistic PG detector mode, incorporate time stamping to distinguish PG and delayed-gammas, and add beam-on/off modulation to determine background signal and clean up the PG measurement. Once this is all in place, we can optimise experiment configuration and protocols for future physical experiments.

A Microsreuctural Approach to Modeling Neutron Transmission Through Single- and Poly-Crystals

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Time-of-Flight (TOF) neutron transmission spectra of single crystal or multi-grain samples feature dips at specific wavelengths where Bragg's law is being fulfilled for distinctive crystal orientations. Thus, the location of the Bragg dips can be used to determine the number and the orientation of the grains intercepting the neutron beam, while the dip shape can provide the distribution of the mosaic blocks per grain. Distinctively, the TOF neutron transmission spectra through ideally random textured polycrystalline samples (small grains and random orientation) are characterized by sudden well-defined step changes in intensity (so-called Bragg-edges) at neutron wavelength locations corresponding to a grain orientation positioned with a specific crystallographic plane in back-reflection, as for larger wavelengths that exceed the Bragg-edge condition the coherent scattering at that corresponding lattice spacing cease to exist. Thus for cases, in which the grains orientations are not random (i.e., nearly all manufactured materials), the preferred crystallographic orientation results in TOF neutron transmission spectra characterized by 'deformed' Bragg-edges at the location of these non-random oriented- planes. In this poster, efforts to model neutron Bragg edge from a single grain to a distribution of grains; modeling the effect of elastic strain on Bragg edges from an applied stress; and the effect of crystallographic texture are presented in ongoing effort to develop models of neutron scattering in real material with the potential to have parameters that can be used to get quantitative results from measurements. This research used resources at the Spallation Neutron Source, a DOE Office Science User Facility operated by the Oak the Oak Ridge National Laboratory.

Machine Learning Module Development for Pydingo

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The neutron imaging instrument DINGO did use Octopus for CT reconstruction since operational until Ocotpus has withdrawn further support. The new developed Pydingo provides once installed easy access to Tomopy and the Astra Toolbox through its GUI which comes in three different sections. The first section handles the repreparation of the raw data including normalisation and selection of region of interest. In addition, a phase retrieval can be selected. The corrected image output will be handled in a second section calculating the centre of rotation, tilt and final reconstructed slices. The reconstruction algorithm is available for parallel and cone beam geometry. In a last section the reconstructed slices can be corrected for beam hardening.

To further improve the reconstruction quality, we suggest applying machine learning (ML) in the data preparation module. A new white spot filter will be the first target. Recognition of white spots in material like cement past and concrete will help to improve porosity analysis for small pore sizes.

In a second step we would like to improve the reconstruction algorithm itself. Hybrid iterative reconstruction methods combining filtered back projection with model based iterative reconstruction are promising alternatives. All new developments will utilise Pytorch as a base for ML in Pydingo. The existing code for Pydingo is using cupy, which limits the compatible computing platforms to Nvidia graphic cards for hardware acceleration. Pytorch offers a broader spectrum like MacOs M1,2,3 based computer and AMD graphic cards as alternatives.

Dynamic Neutron Radiography of Aqueous Foams - Review of Recent Experiments at The NEUTRA Beamline

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Aqueous foam constitutes a complex and fragile research object. It consists of gas bubbles separated by thin liquid films. The interstitial liquid is arranged in a network of channels, connecting the liquid films. The behavior of foam is defined by the interaction of many processes on different length scales, ranging from surfactant sorption on the nanometer scale over liquid film stability, surface-tension dominated topology up to gravity driven convection rolls on the meter scale [Co13]. Since foam is optically opaque, it is not accessible for standard optical measurement techniques and many aspects in foam are not yet understood. In particular, the dynamic behavior of flowing foam and the interaction with drainage of liquid inside the foam is hardly researched.

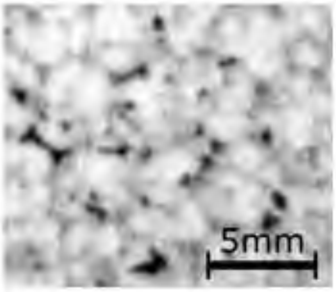

Figure 1: Radiography of aqueous foam with gadolinium particles in the foam structure.

Neutron radiography provides an innovative approach to aqueous foams, as it allows to resolve the liquid distribution inside the foam structure. We have performed dynamic neutron radiography studies on aqueous foam. It allows to quantify the liquid fraction distribution inside the foam with high temporal resolution of up to 10 Hz and sub-millimetric spatial resolution [He18].

When liquid is fed to a foam via a needle, it drains downward due to gravity through the network of interstitial channels. Simultaneously, it diffuses horizontally due to capillary forces. We have measured the horizontal diffusion term, confirming theoretical predictions. Also, vertical transport velocity of liquid in the foam structure was quantified by switching the original water with heavy water [Sk23].

A unique feature in foam is the so-called anisotropic drainage. When a foam is sheared, the interstitial network shows a preferential direction and the draining liquid is deviated horizontally. We have performed neutron radiography of the drainage in a sheared foam and quantified the horizontal deviation of the drainage flux. In that way, we provided the first experimental proof to the theoretical prediction of anisotropic drainage in foam [Sk24].

Adding sub-millimetric gadolinium particles to the foam structure allowed for particle tracking [He19]. We have quantified the removal of such particles from the foam structure under the action of draining liquid. In particular, a clustering of particles was observed, blocking individual liquid channels and moving in an avalanche-like pattern. Such investigations are highly relevant for understanding the role of a froth zone in industrial froth flotation.

Finally, we have employed neutron radiography as a very suitable tool for liquid fraction measurement and performed simultaneous measurements for calibrating other innovative measurement tools based on ultrasound [Em22] and electric conductivity [Zi22].

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Simulated Neutron Radiography of Hydrogen Diffusion Couples Using Unstructured Meshes

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Hydrogen is an important element in multiple components of a nuclear reactor. While hydrogen is beneficial for moderating neutrons in thermal reactors, it detrimentally affects cladding materials when picked-up from coolant water. The more hydrogen migration in materials is understood, the more the behavior of hydrogen can be accounted for in nuclear reactor designs. Neutron radiography can quantify the hydrogen concentration throughout a sample to determine how it evolves as a function of temperature and time. However, calibrating neutron radiography systems for hydrogen quantification is challenging. Creating simulation models of neutron radiography systems can enhance neutron radiography as a tool for quantitatively analyzing hydrogen concentration. The unstructured mesh capabilities of the Monte Carlo n-Particle (MCNP) code allow for complex geometries and spatially varying material compositions at a fine resolution. These capabilities enable neutron radiography simulations for samples with variable hydrogen concentrations and facilitate calibration methods for the quantitative analysis of hydrogen concentration in materials.

Complimentary Relationships Between Neutron Computed Radiography and Digital X-Ray Radiography of Radioactive Specimens

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The Transient Reactor Test (TREAT) Facility is a 19,000 MW reactor located at the Idaho National Laboratory which is used for transient testing of materials and experiments. A neutron radiography facility is installed which allows for low resolution neutron imaging with a capability of items up to 20 cm wide and 400 cm long. Along with the neutron radiography facility, a 370 kV digital X-ray system is located onsite for when X-ray imaging is more practical or when rapid imaging is requested. The X-ray facility can accommodate specimens up to 61 cm wide and 1000 cm long.

This poster discusses the complimentary relationship between transfer-method Neutron Computed Radiography (nCR) and Digital X-ray Radiography (DR) imaging of radioactive specimens along with practical applications for nuclear fuels and materials testing programs. Both nCR and DR images were acquired of inert gas and water filled apparatus containing differing materials at varying radiation levels. Highly radioactive items have no effect on nCR image quality whereas radioactivity has varying degrees of effect in DR. Radioactive items as high as 20 mSv/h have been successfully imaged using X-ray DR methods.

Integration and Evolution of Bimodal X-Ray and Neutron Imaging

Anders Kaestner presenting for Mahdieh Shakoorioskooie

Mahdieh Shakoorioskooie, Eberhard Lehmann, Markus Strobl, Qianru Zhan, David Mannes, Pavel Trtik, Anders Kaestner

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In the dynamic field of materials science, the integration of X-ray tomography into the neutron imaging, stands as a landmark advancement, revolutionizing the non-destructive characterization of materials [1]. This innovative approach harnesses the distinct yet complementary capabilities of each modality.

More than a decade ago, our group led the way into bimodal imaging, introducing instrumental innovations [2] that enabled bimodal imaging [3]with a wide range of applications [3] and advent of similar implementations in other beamlines[4][5]. X-rays, with their adeptness at mapping electron density distributions, provide a contrast based on atomic number variations, whereas neutrons offer a unique window onto the involved nuclei, revealing highly complementary insight with respect to hydrogen content. The establishment of bimodal imaging at two distinct beamlines at the spallation neutron source SINQ, ICON (simultaneous imaging, near perpendicular) [3] and NEUTRA (off-line, parallel) [2], exemplified our pioneering approach.

Early attempts to combine X-ray and neutron datasets relied on simple analytical tools such as bivariate histograms, aiming at identifying correlations between the datasets [6]. This method can effectively highlight areas where the properties detected by X-ray and neutron imaging overlap or diverge, while being limited in producing nuanced single representation of the material.

Advanced fusion methods rely on more complex algorithms, which are based on pixel-level, feature-level and decision-level methods [7], [8]. They allow for the integration of detailed spatial and spectral information from each modality, resulting in a comprehensive and coherent representation of the material's characteristics. They are tailored to capitalize on the strengths of each imaging modality, meticulously addressing challenges such as differences in penetration depth and sensitivity to different material constituents.

A notable example of multi-scale fusion based on pixel-level information is the Laplacian Pyramid Fusion (LPF) [9]. This technique is particularly practiced at merging images that have differences in focus or contain various details at different scales. This is the scenario that we encounter when fusing images captured with different detector systems and varying resolutions. To illustrate the efficacy of this approach, we showcase an example of fusing bimodal images of an archaeological sample, imaged at NEUTRA beam-line.

In conclusion, by combining X-ray and neutron imaging, our research has significantly advanced in materials characterization. While we started with basic methods, we've moved on to more advanced techniques that give us a much clearer view and which has made it easier to study a wide range of materials.

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Highlighting Less Known Muhrec Features

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The tomography reconstruction tool MuhRec was first introduced at WCNR-9 [1] and has evolved in several aspects since. The central task of the tool is to perform tomographic reconstruction of projection data. There are features in both user interface and processing that may be of interest to your work.

The user interface:

- A pixel size measurement tool to make it easier to determine the pixel size of the projection data.
- A file sequence conversion tool that can convert file format, combine repeated acquisitions for each angle, and recombine interrupted and restarted scans with files in different locations and file names.
- Mass reconstruction can be performed from the command line. A useful feature for a time series of tomographs.
- The core components of the preprocessing and the back projector can be imported in python scripts for an alternative implementation or integration in the beamline workflow.

The processing:

- Truncated data can be handled and to some extent be reconstructed beyond the edge
- Tilt series can be reconstructed, making it possible to obtain the 3D information from slabs. This is an alternative method to laminography.
- The skip list tool can identify and exclude under-exposed projections from the reconstruction.
- The code has efficient memory management and runs on a computer with only 2GB RAM.

The code is published as open source, and releases are available for Windows, MacOS, and Ubuntu on GitHub (https://neutronimaging.github.io).

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Performance Evaluation of Neutron Shielding Material For Storage and Shipping Cask of Spent Nuclear Fuel Using Neutron Imaging

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Neutron shielding material is important for storage and shipping cask of spent nuclear fuel, and the demand for neutron shielding materials is steadily increasing because there is not enough space in the temporary storage anymore. However, Neutron shielding materials required for industrial purposes in Korea are entirely depend on imports. Some research groups have studied and developed Fe based neutron shielding materials for localization. The samples of Fe based neutron shielding materials were fabricated and prepared by ferrous alloy research group of Korea Institute of Materials Science (KIMS). Strong thermal neutron absorbers such as Gd, Li, and B should be included in Fe based neutron shielding materials to increase neutron shielding ability. We have fabricated new type of neutron shielding materials with KIMS, and we measured their neutron transmission and macroscopic cross section to evaluate neutron shielding ability by neutron imaging. Neutron imaging experiments were performed to measure neutron transmission intensity of prepared samples using Hokkaido University Neutron Source (HUNS) and Research reactor of Korea (HANARO).

Investigation of the PEM Fuel Cells Performance Behavior Using HANARO

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Neutron has been used in various research fields, and it is a potent tool for improving the performance of PEM Fuel cells. Several techniques have been applied for fuel cell study, but neutron is essential because neutron penetrates metals well and is very sensitive to hydrogen. PEM Fuel cells have many issues, but water management in low-temperature fuel cells is still crucial because it can affect performance and durability. When the water is too much, the performance of PEM Fuel cells is lower at high current density regions because of the flooding problem. In addition, there are also problems such as carbon corrosion and platinum dissolution. On the other hand, when the water content is less, it can make dry conditions, and the performance can be lower because of lower proton conductivity. Therefore, it is important to understand the water behavior and its effect on the operating fuel cells.

In this study, we investigate the performance behavior according to various onditions, such as electrode configurations, gas diffusion layer porosity, and thickness by using neutron and other methods. Korea Atomic Energy Research Institute (KAERI) has a powerful neutron source (HANARO) and it has been contributing to improving the performance and durability of fuel cells by using different neutron beam instruments (Neutron Radiography Facility, Residual Stress Instrument, and 18M SANS). Based on the results, we can assume that the performance would be dramatically different depending on the characterization of cell materials which would make different water behaviors during the operation.

Preliminary Results of a Bulk Hydrogen Quantification Technique Using Neutron Radiography

Jeff King presenting for J. Zymbaluk

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Zirconium alloys see widespread use throughout the nuclear industry primarily for their relative neutron transparency and corrosion resistance. However, hydrogen accumulated in Zr alloys through eventual waterside corrosion can lead to several detrimental impacts, including complete mechanical failure. So, it is important to understand the driving forces for hydrogen migration in the material. Neutron radiography-based Hydrogen Quantification (NHQ) can provide effective, nondestructive measurements of bulk hydrogen concentrations. The calibration of this technique took place at both the Geological Survey TRIGA Reactor (GSTR) and the Phoenix Neutron Imaging Center. Destructive analysis of samples with known hydrogen concentrations provided calibration data for Zr702, Zircaloy-4, and Zr-2.5Nb samples imaged in NHQ. Preliminary results from the application of NHQ to various diffusion couples are presented, specifically, transient measurements of key hydrogen migration parameters. In this study, NHQ extracts parameters from three distinct sample groups to measure: hydrogen's diffusion coefficient, hydrogen's heat of transport, and the effect of opposing concentration and temperature gradients on the migration of hydrogen. These measurements are in progress on both Zircaloy-4 and Zr-2.5Nb samples.

Introduction of Camera System for CNRF at JRR-3

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The CNRF is a neutron radiography facility using cold neutrons installed in the beam hall of JRR-3 (Fig. 1). A neutron beam, guided from the JRR-3 reactor room to the beam hall by a C2 cold neutron guide tube, is split into three beamlines (reflection angles 0°, 10°, and 20°) using a neutron bender [1]. The CNRF uses that with the reflection angle of 20°, C2-3-3-1 port. The CNRF imaging position is approximately 4 m from the bender, and the beam size is 20 mm (W) × 30 mm (H). The neutron flux at the position is approximately 1.7 × 10^7 n/cm^2/s. Figure 2 shows a photograph of the inside of the CNRF imaging room. The imaging room size is approximately 650 mm (W) × 850 mm (H) × 600 mm (D). A rotary stage and a linear stage for samples are equipped in the room.

At the resumption of JRR-3 operations in 2021 after a 10-year shutdown, only an imaging system using imaging plates (IPs) was available at the CNRF. Although high-resolution images could be acquired, the system was unsuitable for continuous imaging required for computed tomography (CT) scans and dynamic imaging. It was also difficult to perform quantitative analysis from the images. To resolve these problems, we have introduced a new imaging system with a dark box, a scintillator, and a CMOS camera (Hamamatsu Photonics, ORCA Flash 4.0 V3). In this poster, the performance of the imaging system, usage examples of the CNRF, and its results will be presented.

Fig. 1. Photo of the CNRF experimental space.

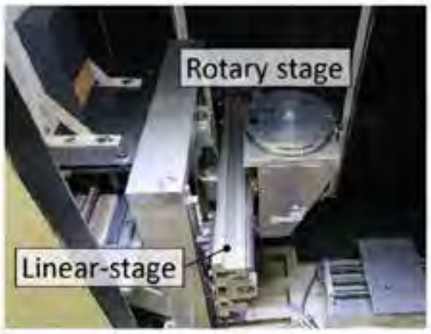

Fig. 2. Photo of the CNRF imaging room.

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Development of Stress and Dislocation Density Imaging Method Using Simultaneous Multiple Bragg-Edge Shift and Broadening Analysis

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Wavelength-resolved neutron transmission Bragg-edge imaging is a powerful tool for measuring strain over a large area of a bulk material with high spatial resolution. So far, we have developed simultaneous multiple Bragg-edges shift (MBE-S) analysis, which enables to analyze the stress parallel and perpendicular to transmission direction which is previously impossible to derive by the transmission Bragg-edge method. This method refines the stress parameters through simultaneous MBE fitting. On the other hand, simultaneous MBE broadening (MBE-B) analysis was developed, and dislocation density and other factors were analyzed [1]. Since simultaneous imagings of stress and dislocation density has not been feasible before, for the purpose of those analyzes, we developed the simultaneous MBE shift and broadening (MBE-S&B) analysis. As a result, fitting analysis for stress with broad Bragg-edges in by plastic deformation is also expected to be improved.

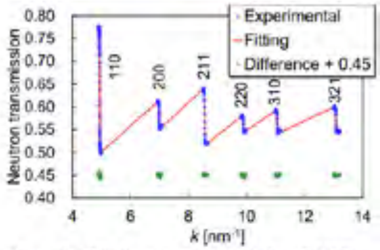

Fig. 1: Fitting result of the MBE-S&B analysis at the tensile of 49 kN.

At J-PARC MLF BL19 TAKUMI, pixelated neutron transmission spectra of an α-Fe plate with two notches at the top and bottom were measured at different tensile loads [2]. In the data analysis, we used the ccWH (corrected classical Williamson-Hall) method for dislocation density analysis of broad Bragg-edges, which is the WH method including a crystal elastic anisotropy correction using the ratio of diffraction Young's modulus. We applied the MBE-S&B fitting analysis to the transmission spectra using refinable parameters of stress, dislocation density and crystallite size, as fitting parameters. Fig. 1 shows fitting result of the MBES&B analysis at a tensile load of 49 kN, and good fitting result were obtained.

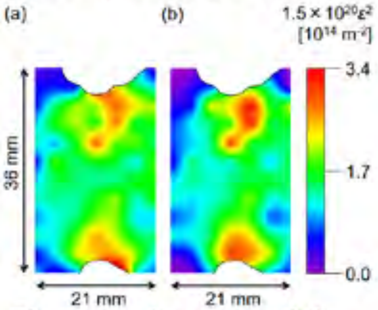

Fig. 2: Imaging results of the $1.5\times10^{20}\varepsilon^2$ value at the tensile of 49 kN by the MBE-S&B analysis (a) and the MBE-B analysis (b).

The differences between the stress analysis results in two directions obtained by the MBE-S&B analysis and the MBES analysis agreed within the resolution of the instrument. The differences in dislocation density and crystallite size obtained by the MBE-S&B analysis and the MBE-B analysis were also small and consistent with previous diffraction studies [1,3,4]. Fig. 2 shows imaging results of $1.5 \times 10^{20}\varepsilon^2$ related to dislocation density. The plastic deformation region at the notches could be clearly visualized, and the result is similar to that of the MBE-B analysis. In summary, the stress analysis results did not change depending on whether or not the broadening effect was considered, but the simultaneous analysis of stress, dislocation density and crystallite size, which were previously impossible before, could be performed by the proposed new method.

In this poster, we report the methodology, and results of quantitative evaluation and imaging.

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Investigation of the Feasibility of a CdZnTe Detector for Neutron Imaging

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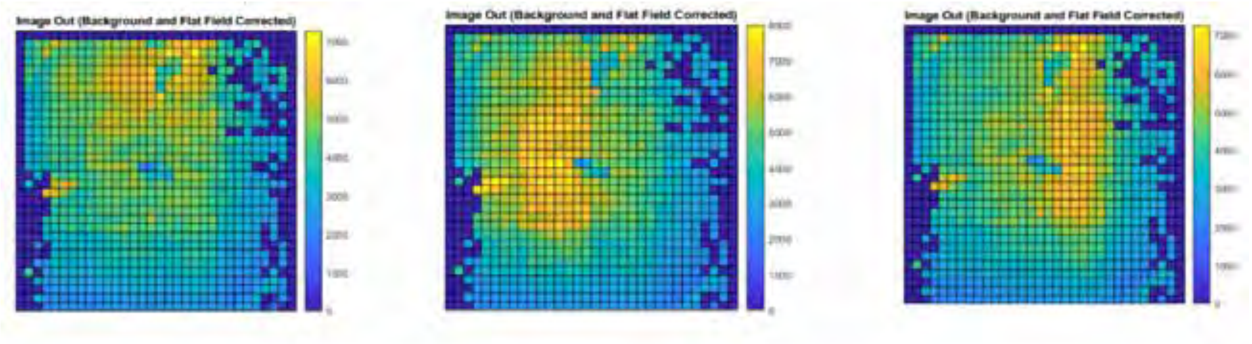
We present the feasibility of using a CdZnTe detector for neutron imaging. CdZnTe detectors have been employed for many gamma-ray imaging studies and showed excellent imaging perfomance. Although Cd has a very high (n,γ) cross section for thermal neutrons, making CdZnTe detectors promising candidate for thermal neutron imaging, only a few studies have been reported to date. A CdZnTe system previously developed for medical imaging applications was set up at the neutron diffraction beam line of the McMaster Nuclear Reactor. Neutron imaging performance and electronics stability is currently under investigation. Preliminary data depicting the detector's response to various cadmium configurations is presented in the figure below, indicating promising results. The system will be upgraded soon to optimize the spatial resolution and improve neutron detection efficiency.



Upper-top exposed Half-left exposed Half-right exposed

Developing Methods for Measuring Spatial Versus Temporal Resolution in Dose Reduced Tomography

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Neutron tomography acquisition time is primarily governed by the low flux of neutron sources. To achieve faster acquisition times, it is necessary to do one or a combination of the following: 1) increase pixel size to reduce shot noise, 2) reduce exposure time decreasing signal to noise, and 3) reduce the number of viewed angles around the specimen which reduces spatial sampling. All three choices reduce achievable spatial resolution or degrade accuracy of reconstruction. To combat these deleterious effects, seeded iterative reconstruction algorithms and machine learning based reconstruction algorithms have been investigated to determine if high spatial resolution can be preserved while greatly increasing temporal resolution. These algorithms require validation and qualification to determine the actual spatial resolution achieved by the algorithm and to ensure that no unexpected structures or artifacts are generated that could have significant impacts on image segmentation and material classification. A phantom, shown in Figure 1, has been developed which allows precision control of sample evolution to characterize time-resolved spatial resolution for this qualification effort. The phantom provides resolution targets with contrast variation for both neutrons and X-rays. This poster will describe the algorithms tested to date and the current efforts and methods being developed to provide real method validation with direct application to user generated experiments.

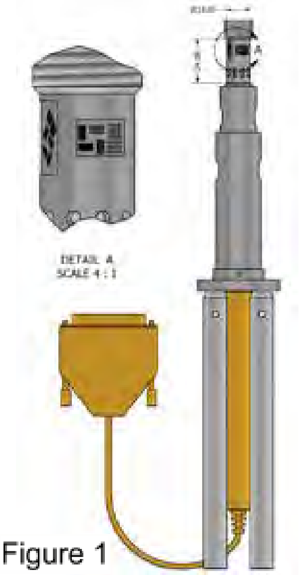

Figure 1

Demonstration of Reconstruction Improvements in Challenging Experimental Bi-Modal Datasets with X-Rays and Neutrons Using a Multi-Layered Joint Regularization Method

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The data fusion of neutron and X-Ray imaging can be used to improve the reconstructed structural information above what can be achieved by using a single modality. By leveraging multiple fusion methods during an iterative reconstruction, it is possible to create an improvement that is greater than the sum of the parts, as each method feeds its improvements into the others creating a virtuous cycle through successive iterations.

A reconstruction method that applies multiple joint regularizations to reconstruct multi-modal data sets was applied to several bi-modal 3D experimental datasets. This method, which regularizes the Simultaneous Algebraic Reconstruction of multiple data modalities with Joint Total Variation and K-Means Cluster Centre Descent, was previously tested on synthetic data. The experimental datasets that the method has now been tested on was a multi-material imaging quality indicator object with thermal neutrons and X-Rays acquired at different resolutions.

The results of applying the multimodal reconstruction, so far, show promise for information recovery and denoising with these non-mutually poor data sets.

Limits in the Neutron Imaging Quantification of Hydrogenous Materials

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The detection of hydrogen in neutron imaging applications is very common due to the high contrast compared to other structural materials around or inside samples. This is a very important advantage compared to X-ray studies, where the contrast for hydrogen is nearly negligible.

The interaction of hydrogen with (thermal) neutrons is via incoherent scattering with very high probability (cross-section). Therefore, hydrogen in a sample is well visible and caused many practical applications like explosives detection, water migration in soil, fuel cells, other porous media and in technical processes (fuel injection, gluing, lubrication, evaporation).

In most applications, the precise quantification of the hydrogen content is requested, and it is worth to spend effort to think about the limits in this approach.

A technical limit is given by the detection system as its signal-to-noise ratio. Only an amount of hydrogenous material can be detected, when it differs from the background by its noise level. This is commonly on the order of a few percent [1].

However, there are much more important effects which limits the precision in the quantification process for hydrogen. Two approaches are possible to derive best possible data: comparison with tabulated cross-section data for the relevant material (e.g. H_2O, ZrH_2, CH_2 or also D_2O) - or the experimental way by calibration to certified materials â€“ under the best possible experimental setup.

Both approaches have their individual problems - and this paper intents to provide details for deeper analyzes and understanding.

Even for very thin layers of hydrogenous materials, where an exponential attenuation approach is still valid, the theoretical cross-sections according the “free-gas” model fails because for slow neutrons the molecular binding has to be considered - resulting in deviating data.

As soon as larger amounts of hydrogenous materials must be investigated, multiple scattering in the sample needs to be considered. Furthermore, the strong component of the scattered neutrons, returning into the area of the sample in the image can disturb the measurements systematically. There are two ways to overcome such problems: placing the sample reasonably away from the detector, where the number of scattered neutrons is low; performing calibration measurements with well-known samples.

Because attenuation coefficients, which are often used to derive the density of the hydrogenous material, are measured as integral over the full neutron spectrum of the beam line, weighted by the detection efficiency, different values are obtained at different facilities. Therefore, the calibration process is urgently needed for each individual investigation, if quantification is desired.

The paper is based on own practical experiences and shows results of successful, but also failing interpretations of neutron imaging data.

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Lithium-Containing Semiconductors for Neutron Imaging

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In the last decade, there have been a handful of publications discussing the neutron-sensing properties and potential of lithium-containing semiconductors for neutron imaging applications [1-4]. Lithium-containing semiconductors provide the potential for high spatial and temporal resolution, excellent gamma discrimination capability, and an excellent neutron utilization factor (detection efficiency). The ability to meet all these needs in a neutron detection system is typically not possible, but in this poster, we will outline why lithium-containing semiconductors hold great promise to enhance the scientific outcomes of neutron radiography, tomography, and/or energy-resolved imaging. First, we will discuss the basic properties of lithium-containing semiconductors, followed by basic electronic pulse processing needs. Then, we will discuss current efforts to improve the performance of ultra-high-resolution neutron imaging systems (time-to-image) as well as larger area imaging plates for neutron diffraction facilities. Finally, we will discuss the potential future of lithium-containing semiconductors as a staple in neutron scattering facilities.

Below is plots of simulated neutron radiographs utilizing pattern classification techniques to enhance the spatial resolution beyond that of the intrinsic range of the secondary charged particles in the ^{6}Li(n,^{3}H)^{4} He reaction, which is approximately 34 µm on the imaging plane. The data provided below, which includes electronic noise and charge collection losses, indicates that a very high spatial resolution is possible using lithium-containing semiconductors.

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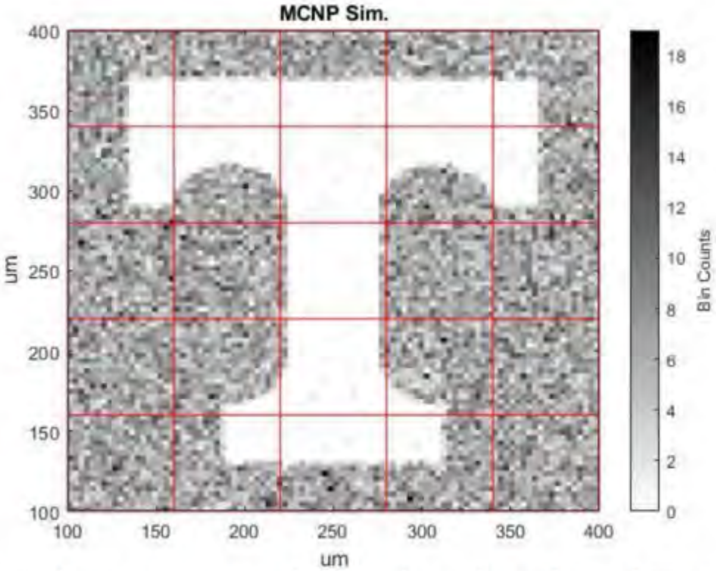
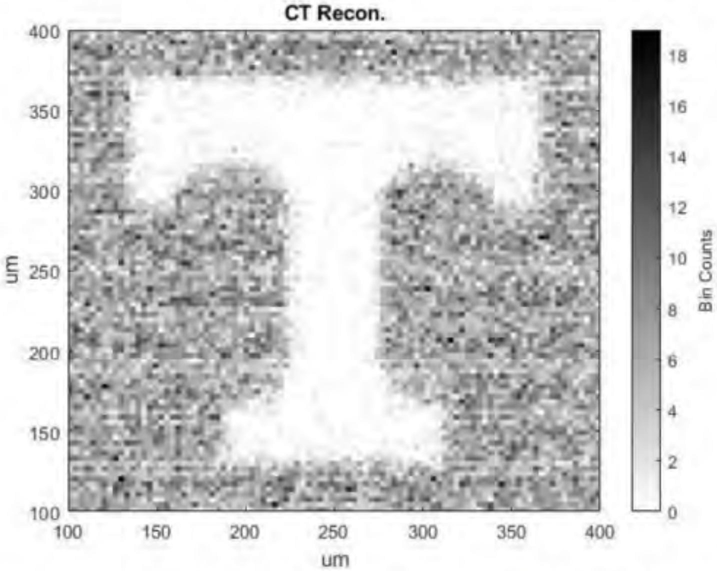


This image represents the neutron interaction location using a thermal neutron beam impinging on a gadolinium University of Tennessee-Knoxville Power T. The detector is a $LiInSe_2$ semiconductor. This data was used to evaluate our spatial-resolution-enhancing algorithm on the expected response of lithium-containing semiconductors. The red grid lines correspond to a sort of symmetry space required for the reconstruction process using pattern classification.



This image represents a coarse tree reconstruction after accurately simulating the motion of the secondary charged particles in the neutron capture of ^{6}Li (i.e., 4π emission and Bragg curves), tracking of signal formation using the Shockley-Ramo Theorem, to include charge trapping, and the resulting signal formation across strip electrodes (width/pitch of 20/30 μm).

Exploring Spatial Resolution Enhancements on IMAT for Steel Corrosion Studies

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Surface imaging is crucial to elucidate degradation of steel materials in combination with chemical and electrochemical characterization. This combined approach allows us to understand and quantify corrosion processes in carbon dioxide transport industries. Corrosion has been responsible for pipeline failures with detrimental human and environmental effects. Two main types of corrosion affect carbon steel in CO_2 environments, general and localized corrosion. Siderite ($FeCO_3$) is the main product of general corrosion, formed from the dissolution of iron from steel, but the most harmful type of corrosion is localized corrosion or pitting, due to its stochastic nature, and up-to-date unknown process.[1,2] Although neutron imaging offers a variety of benefits including deeper steel analysis (millimeters) and high sensitivity to some light elements (e.g., hydrogen), effort is required to improve the spatial resolution for white beam and energy-resolved imaging. Our aim with this work was to investigate approaches to enhance the current spatial resolution (60 µm) on IMAT instrument (ISIS neutron source at the Rutherford Appleton Laboratory, UK) to support the imaging of corrosion layers between 20 µm and 40 µm which allow us to get a deeper understanding of corrosion processes.

Therefore, we have explored two approaches to improve spatial resolution on IMAT. For the first approach, we have used a fiber optics taper[3] as an attachment to optical camera boxes (CMOS and CCD) for white beam imaging. The fiber optics taper works on the principle of optical magnification (here: 6:1) without requiring significant changes to the detection system. The resolution was evaluated in 2D and 3D using a Siemens star and steel spheres, respectively, and by applying the Modulation Transfer Function approach. However, obtaining good white-beam contrast is nevertheless challenging because wavelength-averaged attenuation coefficients of steel and siderite are not sufficiently different. For the second approach, we used two Timepix-based detectors (Berkley MCP[4] and TPX3Cam-LumaCam[5]) with different spatial resolution settings for wavelength-resolved imaging to exploit the diffraction contrast of Bragg edge imaging. A better spatial resolution was achieved when event centroiding approach was employed.

Our results show that spatial resolution of 30 µm is now achievable on IMAT for practical imaging applications. Unwanted edge enhancement effects are also avoided. This has significantly improved from the current 60 µm and 110 µm for white beam and energy-resolved imaging at the facility, however at the expense of reduced field of view. This technical development will therefore help to advance corrosion and degradation studies of steel using neutron imaging at this facility when studying corrosion layers thicker than 20 µm.

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Revaluation of a Formula Converting Neutron Transmission Bragg-Edge Broadening to Vickers Hardness of a Ferrite/Martensite Steel

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Neutron transmission Bragg-edge imaging is a technique to visualize a large field-of-view distribution of information on bulk crystalline microstructure of materials from Bragg-edge neutron transmission spectra caused by neutron diffraction phenomena. The full width at half maximum (FWHM) of a crystal lattice plane spacing distribution of a ferrite/martensite steel is obtained through the broadening analysis of Bragg-edge profile fitting. In a previous study [1], it was shown that there was a linear relationship between the FWHM of a crystal lattice plane spacing distribution and the Vickers hardness (HV) of quenched JIS-S45C steel, and a conversion formula to deduce the HV from the FWHM (unit: nm) was obtained, i.e.,

$$\mathrm{HV} = 1.96 \times 10^5 \times \mathrm{FWHM} + 71.3.$$

However, an excessive HV value was deduced using this conversion formula in the Bragg-edge martensite imaging experiment on a Japanese sword due to deviation from linearity over HV = 700 and insufficient knowledge on analysis at the early-stage study. In addition, the results of other experiments for JIS-SCM440 steel did not follow the linear relationship. Therefore, the purpose of this study was to reanalyze the relation between the FWHM and the HV of quenched JIS-S45C and JIS-SCM440 based on the knowledge of analysis procedures accumulated in recent years and to revaluate the conversion formula between the FWHM and the HV.

In order to ensure stable and accurate fitting, we checked the analysis results with various fitting wavelength ranges and initial parameter settings, compared to previous results. As a result, the results of this study showed a larger FWHM for HV compared to the previous results. By adding the results of quenched JIS-SCM440, we were able to obtain a new formula based on a sigmoid function,

$$\mathrm{HV} = \frac{524}{1 + \exp\left(-167 \times \mathrm{FWHM} - 0.0207\right)} + 200.$$

Fig. 1 shows the relation between the FWHM and the HV of JIS-S45C and JIS-SCM440 with a new conversion formula. By using a sigmoid function, the overestimation of the HV was overcome. However, to make the formula more reliable we need more data over HV = 700.

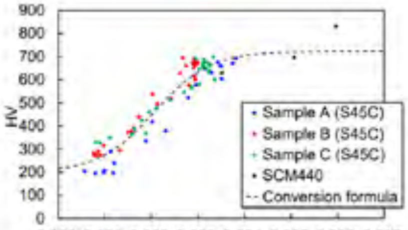

Fig. 1: Relation between FWHM and HV of JIS-S45C and JIS-SCM440 with new conversion formula.

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Study of Failure Mechanisms in Additively Manufactured Steel Samples using Grating Interferometry and Bragg Edge Imaging

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Additive manufacturing (AM) allows prototyping parts with a reduction of wasted material. It is also rapidly evolving towards manufacturing complex, functional parts in the space and aviation industry. One standard method of AM is laser powder bed fusion (LPBF), which selectively welds metal powder layer by layer using a laser. As with conventional manufacturing methods, a deviation from the ideal manufacturing parameters causes defects. These defects reduce the mechanical strength of the part and lead to fractures under load. While destructive methods unravel defect structures in parts before or after failure, they do not allow, e.g., the tracking of the defect evolution over time under mechanical load. Consequently, there is a strong demand for non-destructive techniques in investigating additively manufactured parts. In this context, most available techniques, such as X-ray CT, active infrared thermography, or ultrasonic testing, show limitations in the accessible length scales or locations of the defects.

In our studies, we used neutron grating interferometry (nGI) and Bragg edge imaging (BEI) to study the change in material properties in AM samples with and without deliberately induced defects under tensile load. In Fig.1 we show the evolution of a fracture measured with nGI in a defect free sample under increasing tensile loading.

The defects considered in our contribution are lack of fusion defects, which are volumes with unmelted metal powder. The density and, therefore, linear attenuation coefficient in the lack of fusion defects deviates little from the defect-free zones. Hence, standard neutron radiography cannot visualize the lack of fusion defects.

Here, the scattering contrast (DFI) detected by nGI allows us to visualize the growth and change of the defect as the scattering contrast of the non-melted metal powder is different compared to the melted powder [1-4]. Next to the growth of the defect due to applied load, BEI allows the investigation of the overall change of the material texture and phase composition.

Our contribution will show how the two measurement techniques complement each other and which conclusions can be drawn from our results.

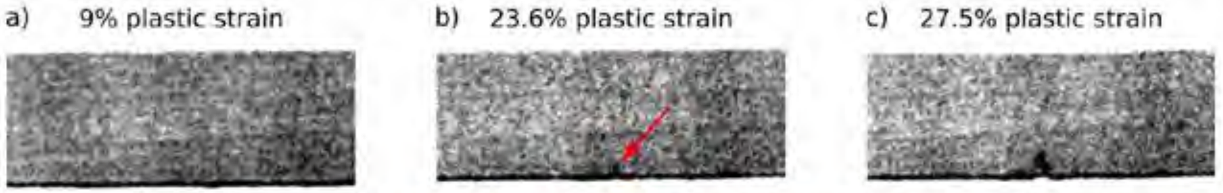
a) 9% plastic strain b) 23.6% plastic strain c) 27.5% plastic strain

Fig. 1: DFI signal of a 1.4404 steel sample under increasing load, causing elongation of the sample as well as formation of fractures in the material (bottom center). The starting point of the fracture is detected at a plastic strain of 23.6 %, after which the growth of the fracture can be observed. Starting from a plastic strain of 27.5 % the fracture rapidly grows, leading to the failure of the sample.

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Hydrogen Transport and Evolution in Ni-MH Batteries by Neutron Imaging

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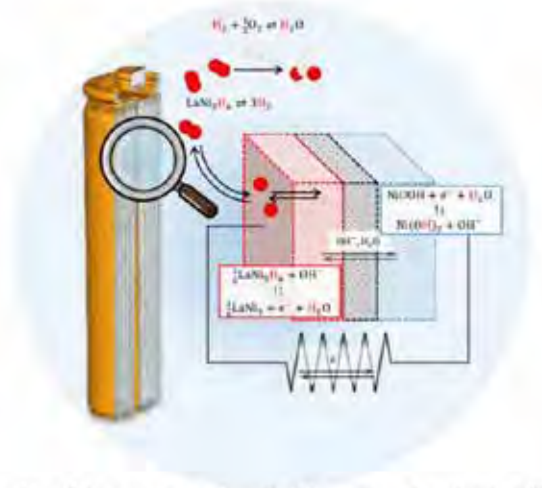

Figure 1: Schematic overview of the processes visualized by neutron imaging in a NiMH-Battery in operation

The transition to renewable energy sources relies on seasonal energy. Nickel metal hydride batteries, invented at the end of the last century, are established batteries without the use of precious and highly hazardous materials. Despite great advantages such as high power-density and easy scale-up, NiMH battery are currently no option as seasonal storage because of various side reactions leading to great efficiency losses such as self-discharge. The latter stems from the unavoidable hydrogen background pressure of the hydride used. Furthermore, hydrogen/oxygen generation occurs during overcharging or over-discharging leading to efficiency losses.

Despite providing valuable insights, the results of standard analysis on the individual components cannot be simply extrapolated to the full operating system. Therefore, non-destructive, and high-resolution approaches that allow the investigation of the full system are desired. Neutron radiography and tomography combined with electrical monitoring of the state of charge of commercial Ni-mischmetal hydride batteries were used to follow the exchange and transport of hydrogen under operating conditions. This non-destructive approach allowed both the quantification of the hydrogen distribution in the electrodes in 4D, and the distinction between the electrochemically exchanged hydrogen and the hydrogen gas pressure generated by side reactions, as a function of the applied potential and current. One of the most counter-intuitive observations is that the generation of hydrogen gas during discharge depends on the charging state of the battery, which is discussed with respect to the hydrogen-matter interactions taking place in the battery.

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Evaluation of Laser Shock Peening Strategies on Steam Turbine Blades Using Bragg Edge Strain Mapping

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The fir-tree-shaped turbine blade roots are one of the critical parts of steam turbines for electrical generators. It maintains the attachment of the blade while being subjected to high centrifugal stress as well as cyclic loading and exposed to wet environment and dynamic thermal loading. Therefore, the part is susceptible to failure modes such as high and low cycle fatigue, stress corrosion cracking and corrosion fatigue. To mitigate that, mechanical surface treatment including laser shock peening has been introduced. While application of laser peening to a flat surface is well researched, its use for components with more complex geometries, such as the turbine blade root, is less explored. Additionally, characterisation of residual stress in such complex geometries can be challenging. In this study, we present the evaluation of peening strategies of turbine blade root using Bragg edge strain mapping. 2D slices of the component is prepared and peened using different strategies, and measured on the IMAT beamline at ISIS Facility, UK. The results, shown in Fig. 1, highlight the value of Bragg edge strain mapping for evaluation of manufacturing processes, especially on components with complex geometries. Advantages and limitations of the technique will be discussed.

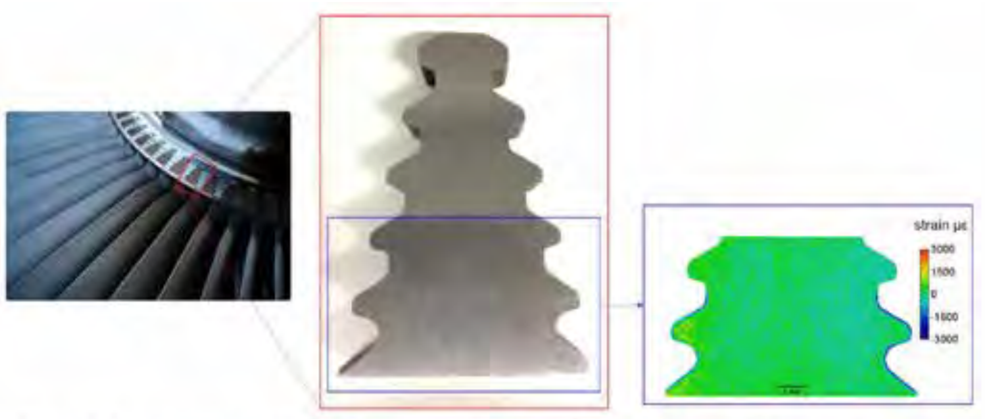

Figure 1. Strain mapping of laser shock peened 2D slice of turbine blade root. Compressive strain is indicated by the blue region on the surface of the specimen.

Multi Modal/Multi-Probe Radiography for Small and Medium Scale Dynamic Experiments

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The increasing complexity of dynamic experiments in condensed matter, fluid, warm dense matter, plasma and ICF physics at all experimental time and spatial scales continues to demand similar improvement in diagnostic systems.

While the traditional, and generally justified, approach to diagnostic development has been to optimize each diagnostic individually, the future, especially for the most complex (and costly) experiments, may lie in the development of techniques to simultaneously co-optimize, employ, and then co-analyze the data from, multiple diagnostics. The 'Multi-Modal' diagnostics concept combines data from, sometimes quite different, techniques to gain a higher fidelity understanding of the experiment. 'Multi-Probe' radiography is one example of a multi-modal diagnostic system that is being explored in Los Alamos National Laboratory

Radiographic techniques most often employ one probing species (x-rays, protons, electrons, or neutrons), and have been highly optimized for each species, and sometimes specialized to specific experiments. Since the interaction physics of the probe with the target materials differs with probing species, the information mapped from the target to the imaging detector may be very different. For example, high energy x-rays map high Z-number material with high fidelity while neutrons map low- Z-number material more effectively. Conceptually, near simultaneous, point-projection probing with multiple species may produce a much more complete description of the dynamic experiment than can be gained from mapping with any single species.

Similar improvements can potentially be gained by mapping with significantly different energies of a single probing species called 'multi-color' radiography.

Realizing the advantages of multi-species radiography involves understanding a complex parameter space including: source physics, source technology, practical experimental footprints, probe-to-probe interactions and detector sensitivity and discrimination. Los Alamos is in the early stages of navigating that complex parameter space.

Petawatt (PW) laser driven x-ray and particle sources are one attractive technology for multi-species radiography because they can produce probes of x-ray and particle species without the need for a different source or accelerator technologies for each. Furthermore, the richness of laser-matter interactions has spawned a world-wide community of university, laboratory, and commercial research institutes where work is constantly improving understanding and performance of PW lasers and accelerators. The rapid development of x-ray tomography for medical applications has provided innovations in both detector technology and 3-D image analysis, including machine learning assisted analysis contribute important capability.

This overview poster will outline the Los Alamos program of assessment, experiments and analysis aimed at evaluating the maturity of multi-species radiography.

Hydrogen Diffusion Studies in Zr-2.5%Nb Alloy Pressure Tube Material Using Neutron Radiography

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Hydrogen embrittlement is a life limiting factor for Zr2.5%Nb alloy used in PHWR pressure tubes. Reactor components during their lifetime pick up hydrogen produced as a byproduct of waterside corrosion. Hydrogen entering the metal matrix above the solid solubility limit precipitates as a brittle hydride phase ultimately degrading component performance. The hydrogen that enters the metal matrix is highly mobile and quickly redistributes itself under concentration, stress or temperature gradients leading to formation of hydride rims, blisters or delayed hydride cracking. Modeling of hydrogen diffusion requires prior knowledge of the various diffusion parameters. In this work we have evaluated hydrogen diffusion parameters for Zr-2.5%Nb alloy used as pressure tube material for Indian PHWRs using Neutron Radiography.

Neutron imaging is used as a non-destructive method to estimate the hydrogen content in zirconium alloys. It has the advantage of good spatial resolution, high sensitivity and fast data acquisition. Thermal neutrons have typically high attenuation for low Z materials like hydrogen and so they can be used for imaging low Z material inside high Z materials. As the attenuation of zirconium hydride is an order higher than that of pure zirconium, we can use neutron imaging to quantify the hydrogen content in zirconium.

The present studies have been performed at Neutron Imaging Beamline at Dhruva reactor, India. The hydrogen diffusion parameters, namely, diffusion coefficient and activation energy have been evaluated for Zr2.5%Nb alloy under concentration gradient in axial, circumferential and radial directions. The experimental results will be discussed in detail in this paper.

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Visualization of Solid-Liquid-Gas Multiphase Flow for Understanding the Phenomenon of Core Debris Self-Leveling Using Neutron Imaging

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This study presents a novel visualization technique utilizing neutron imaging to investigate the solid-liquid-gas multiphase flow dynamics critical for understanding the self-leveling phenomenon of core debris in nuclear reactors. The self-leveling process, a key safety mechanism during severe accidents in light water reactors (LWRs), involves the redistribution of molten core materials to enhance heat removal and prevent reactor vessel failure. However, the high neutron attenuation of light water complicates the direct observation of this process, necessitating the use of alternative materials to simulate the multiphase flow. In our approach, heavy water (D_2O) is employed as the liquid phase to mitigate neutron attenuation issues, while lead-bismuth eutectic (LBE) particles represent the solid phase, and air serves as the gas phase. This selection of materials allows for the effective visualization of the interactions between phases under neutron imaging, providing insights into the fluid dynamics and particle distribution within the flow. The experimental setup includes a rectangular flow channel designed to simulate the conditions within a reactor core during a severe accident scenario. Neutron imaging, conducted at a high-resolution neutron imaging facility at the JRR-3, captures the dynamic behavior of LBE particles suspended in D_2O, with air injected to create the three-phase flow. The imaging technique provides unparalleled clarity in observing the phase separation, distribution of solid particles, and the overall flow pattern, which are critical for modeling the self-leveling process.

The results demonstrate the viability of using neutron radiography combined with this unique material selection for studying multiphase flow in nuclear safety research. The visualization reveals significant insights into the mechanism of self-leveling, including the role of particle size, density differences between phases, and the impact of gas injection on flow dynamics. These findings contribute to a deeper understanding of the self-leveling phenomenon, offering potential improvements in reactor safety design and emergency response strategies.

A Synergy of Neutron Imaging and Diffraction Methods for Cultural Heritage Research at ANSTO

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A major challenge in the investigation of material documents of cultural, historical and archaeological significance is the need of non-invasive scientific analytical methods to better understand our past thought the characterization of ancient artefacts while preserving their unique value and integrity for transmission to future generations. Although laboratory-based techniques can provide valuable information, in some cases these conventional methods present strong limitation in term of penetration depth and representativeness.

Neutron imaging and methods have emerged as a highly sensitive, accurate and non-invasive tool to characterize a variety of ancient artifacts, qualitatively and quantitatively.

In this paper a selection of relevant cross-disciplinary studies conducted at the Australian Nuclear Science and Technology Organisation (ANSTO) using a synergy of neutron methods and undertaken in collaboration with Australian and international stakeholders will be showcased: from the advanced manufacture of arms and armours to the secret of votive items, through invention of coinage.

Operando Visualization of Mass Transfer in a Sodium-Zinc Molten Salt Battery with a Liquid Electrolyte

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To bring the Na-Zn molten salt battery to market, several unresolved issues must be addressed, including self-discharge, migration of Na away from the current collector, and electrolyte 'creeping'. The Horizon 2020 project SOLSTICE[1] aims to deliver a working battery prototype. To support this objective, a small-scale experimental cell has been built for fundamental research. The cell has been designed to allow for in situ radiographic imaging of its interior. The objective is to charge and discharge the cell during dynamic X-ray or neutron radiography, in order to observe the mass transfer of electroactive species and any flow that occurs during cycling. The focus is on how these phenomena depend on the geometry and chemical composition of the different cell components, such as the positive and negative current collectors.

Neutron radiography experiments were conducted at the Paul Scherrer Institut (PSI) in Villigen, Switzerland, using the NEUTRA instrument of the neutron spallation source SINQ. The in situ experiments had a 1-second exposure time and employed a 200 µm ^{6}LIF/ZnS scintillator. Figure 1 shows a representative cycling profile, with neutron radiographs taken at the start of the experiment (bottom left), at full charge (middle), and at almost discharged state (top right). In this example, the cell was charged at a rate of 800 mA for 20 minutes until it reached a capacity of 250 mAh. It was then discharged at the same rate until its cell potential reached the lower cut-off voltage of 0 V. A white meniscus is clearly visible at the current collector, which is attributed to the displacement of the salt electrolyte by liquid sodium. During charging, the sodium layer gradually grows and spreads from the centre of the current collector. It remains stably attached to the disc and resists moving around the edges or floating to the surface. The top right shows the cell at an almost fully discharged state, after most of the Na had been consumed. A thin sliver of Na attached to the current collector can also be seen. Generally, metallic Na tends to remain at the current collector. In depth analysis of the obtained data will be presented at the conference.

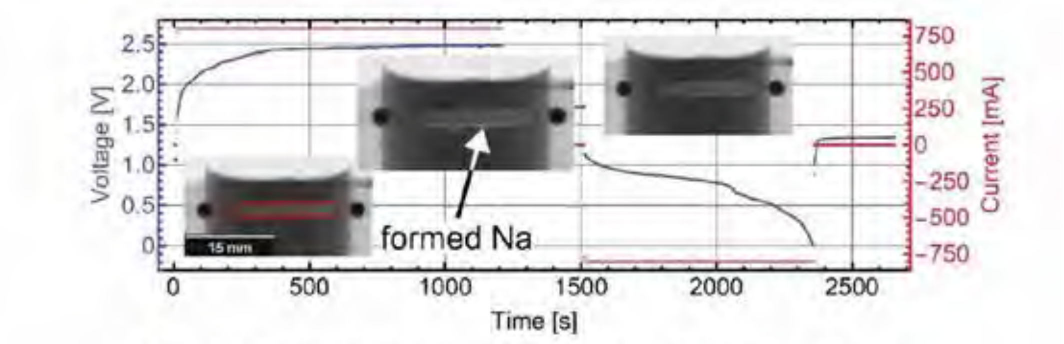

Figure 1. A cycling profile with corresponding neutron images showing sodium formation.

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[1] https://www.solstice-battery.eu/

Neutron Imaging Measurements with D-D and D-T Neutron Generators

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As part of the renewal of some experiments around the reactor, the previous neutron radiography system based on a liquid nitrogen cooled CCD-camera was replaced. Therefore, a new, modern unit was created. During the designing and successive construction of the new radiography station, special attention was paid to the function of the TU Wien as a research facility. Instead of purchasing a commercial system, a special design was created based on plans from the Technical University of Munich, where a similar system is already in use. The new neutron radiography station is a cost-effective instrument that fully corresponds to the state of art technology. This was achieved by using a 3D printer to manufactur most of the parts in-house. The built-in CMOS astro camera with peltier cooling is also a significant improvement over the former system. With the self-developed measuring software and the specifically build controller, a complete and powerful facility was created. By that, a modern instrument for teaching and research is on hand at the TU Wien to perform radiography and tomography with neutrons.

Development of Laser-Based Fast Neutron Sources for MeV Radiography

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Neutron radiography is an invaluable technique for non-destructive evaluation of hydrogen-rich materials such as organic materials or plastics. MeV neutron sources can be particularly useful for radiographing complex multi-material objects (e.g. low-Z combined with high-Z). Typical sources used for neutron radiography have a large source size (mm-cm), reducing the resolution capability of the radiograph, and integrate from a continuous or long-pulse-duration (microsecond spallation) source, preventing radiographs of fast-changing dynamic systems. Laser-based sources have the potential to reduce source sizes (sub-mm) and exceed the average flux of currently availably sources, opening up a new phase-space for neutron radiography.

A new generation of laser technology is being brought online internationally that will be capable of high-power (10 PW) high-repetition rate (1-10 Hz) operations, and open new opportunities for laser-driven neutron radiography sources. Here, we discuss our development of laser-based neutron sources in two different regimes to bridge the gap between current and future laser architecture; high-power (500 TW) shot-on-demand (~0.001 Hz) experiments investigating source size manipulation, and moderate-repetition-rate (0.5-1 Hz) investigating extended operation neutron production. We discuss how this new generation of lasers should enable higher neutron yields ($\geq 10^9$ neutrons/sr/shot) to generate single-shot radiographs, and draw parallels with proven laser-driven x-ray radiography to discuss the anticipated spatial and temporal capability of these future laser-driven neutron radiography sources.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and was supported by the LLNL-LDRD Program under Project No. 22-ERD-022.

Release Number: LLNL-ABS-860240

Advancements in Neutron Radiography for Hydrogen Characterization in Irradiated Zirconium Alloy Cladding

Pavel Trtik presenting for Liliana I. Duarte

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High-resolution neutron imaging (HR-NI), using PSI's Neutron Microscope, is a valuable non-destructive tool for quantitative hydrogen concentration and distribution analysis for both, un- and irradiated nuclear fuel claddings, with a sub-10 µm spatial resolution and sub-10 wppm hydrogen sensitivity. In this respect, HR-NI has allowed unique investigations of hydrogen in highly radioactive fuel cladding sections after service in nuclear power plants and after thermomechanical testing at hotlab facilities.

Zirconium alloys are the main material used as fuel cladding in nuclear reactors due to their excellent compromise between mechanical stability, corrosion properties and low neutron cross section. As the fuel cladding is the first barrier against the release of highly radioactive fission products, ensuring its structural integrity during operational lifetime and during intermediate dry storage after service is paramount. During reactor operation, the zirconium-based claddings undergo water corrosion, and a part of hydrogen (by-product of corrosion) diffuses into the metal. Given the limited solubility of hydrogen in zirconium alloys, excess of hydrogen leads to the formation of brittle hydrides, significantly impacting the mechanical properties of the cladding by reducing its fracture toughness and ductility. The number of hydrides and their orientation with respect to mechanical loading play a pivotal role for the increase of spent fuel failure risks, for instance during unloading procedures, handling, or transportation also after intermediate dry storage. The non-uniform distribution and accumulation of hydrogen/hydrides, attributed to the high mobility of hydrogen interstitial atoms, further increase the risk of strong local embrittlement. In this context, the knowledge about the hydrogen concentration and distribution within the cladding is of utmost importance. HR-NI has brought significant advances for the understanding of hydrogen behavior under thermomechanical loading that simulates spent fuel rod processing after operation. Recent advancements in hydrogen characterization using HR-NI and respective challenges and advantages will be presented.

Direct Observation of Water Uptake by Hygroscopic Liquid Droplets with Neutron Radiography

Pavel Trtik presenting for Hyeonjun An

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Hygroscopic liquids readily absorb water vapor from the ambient air, forming binary liquid systems, such as glycerol-water mixtures. Absorbed water may be distributed inhomogeneously, triggering complex mass transport phenomena like convection, diffusion, and Marangoni flow. While these have been explored via particle image velocimetry and numerical simulations, quantitative characterization and understanding of how material composition evolves have remained challenging. In this work, our neutron radiography quantifies the spatiotemporal distribution of water in hygroscopic droplets on a solid substrate by leveraging the contrast between deuterated hygroscopic liquid and water of natural isotopic composition. We investigate droplets of different liquids, varying their volume, contact angle on substrates, and the direction of gravity. Our study demonstrates that gravity may affect the water distribution, e.g., resulting in a water gradient even in sub-millimeter droplets, according to the liquids' physical properties such as density and viscosity.

Upgrade of NEUTRA Instrument - a Project Update

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The upgrade of the NEUTRA instrument [1] represents a complete reconstruction of the beamline including a redesign of the shielding bunker. The poster will summarize the aims and review the status of this ongoing project whose realization is currently planned for the upcoming shutdown period of the Swiss neutron spallation source (SINQ).

Reference:

[1] P. Trtik, et al., J. of Phys.: Conf. Ser. 10.1088/1742-6596/2605/1/012001

Simultaneous Neutron and X-Ray Tomography for Visualization of Graphite Electrode Degradation in Fast-Charged Lithium-Ion Batteries

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This abstract is re-produced with permission from Cell Press for the following article: Yusuf, Maha, et al. "Simultaneous neutron and X-ray tomography for visualization of graphite electrode degradation in fast-charged lithium-ion batteries." Cell Reports Physical Science 3.11 (2022).

Advanced battery characterization using neutron and X-ray-based imaging modalities is crucial to reveal fundamental degradation modes of lithium-ion batteries (LIBs). Taking advantage of the sensitivity of neutrons to some low-Z (Li) and X-rays to high-Z materials (Cu), here we demonstrate the viability of simultaneous neutron- and X-ray-based tomography (NeXT) as a non-destructive imaging platform for ex situ 3D visualization of graphite electrode degradation following extreme fast charging (XFC). In addition, we underscore the benefits of the simultaneous nature of NeXT by combining the neutron and X-ray data from the same sample location for material identification and segmentation of one pristine and two XFC-cycled graphite electrodes (9C charge for 450 cycles). Our ex situ results and methodology development pave the way for the design of NeXT-friendly LIB geometries that will allow operando and/or in situ three-dimensional (3D) visualization of electrode degradation during XFC.

WCNR 12

PRESENTATION ABSTRACTS
WEDNESDAY, 5 JUNE 2024

WEDNESDAY, 05 JUNE 2024

Pre-session

8:00	Welcome & Announcements

Energy & Environment | Chair: Daniel Hussey

8:10	**Maha Yusuf** | In-Situ, Non-Destructive, 3D Neutron Imaging of Lithium Plating Following Extreme Fast-Charging of Full-Cell Lithium-Ion Batteries
8:30	**Anders Kaestner** | Tomographic Study of Rhizobox Dynamics
8:50	**Cedric Qvistgaard** | White Beam Polarized Neutron Imaging of Weak Ion Currents in Energy Devices Via Induced Magnetic Fields
9:10	**Yuto Obayashi** Presenting for **Hideki Murakawa** | Visualization of Liquid Water Behavior in a Polymer Electrolyte Fuel Cell Under High-Temperature Operation Using a Neutron Radiography
9:30	Break

New Facilities | Chair: Takenao Shinohara

10:00	**Jana Matouskova** | TRIXIE -- Development and Construction of a New Neutron Imaging Instrument in The Czech Republic
10:20	**Andreas Meyer** | A New Thermal Neutron Imaging Instrument at the Institut Laue Langevin
10:40	**Afaf Ouardi** | Final Design of Neutron Imaging System "NERA" at the Maamora Reactor
11:00	**Naoya Odaira** | Experiments and Numerical Simulations on Fast Neutron Imaging
11:20	**Frederico A. Genezini** | Neutron Radiography at the Energy and Nuclear Research Institute/Brazil - IPEN: the Story So Far and Future Perspectives
11:40	**Manuel Morgano** | ODIN @ESS: Commissioning of the Instrument
12:00	**Hassina Bilheux** | Commissioning the VENUS Imaging Beamline at the Spallation Neutron Source
12:20	Day 3: Working Lunch: Cultural Heritage Discussion led by Aaron Craft

VENUS Plenary | Chair: Hassina Bilheux

14:00	**Aaron Hanks** | The Construction of the VENUS Imaging Instrument at the Spallation Neutron Source: the Engineering Perspective
14:30	**Jean Bilheux** | Data Workflow and Software Tools at VENUS
15:00	**Anton Tremsin** | Overview of Science Capabilities of VENUS Beamline
15:30	**Adrian Bruegger** | The Future CUPI^{2}D Beamline at the STS: A General Update Including Optics Design
16:00	Break

Nuclear Engineering | Chair: Winfried Kockelmann

16:30	**Sarah Weick** | In-Situ Neutron Radiography with Hydrogenated Tensile Samples in the INCHAMEL Facility
16:50	**Aaron Colldeweih** | Post Ramp and LOCA Simulation Characterization of Cr-Coated Zircaloy-4
17:10	**David Chichester** | The Fuel Motion Monitoring System at TREAT - Current Status and Future Plans
17:30	**Markus Strobl** Presenting for **Florencia Malamud** | Spatially Resolved Texture Characterization of Cold-Rolled Zircaloy-4 Cladding by Bragg Edge Imaging
17:50	**Youngju Kim** | Observation of Nano-Void Coalescence in Hydrogen-Fatigued Vessel Steel Using Neutron Dark Field Imaging
18:10	**Sven Vogel** | Pulsed Neutron Characterization of Irradiated Fuels at Lansce
18:10	Adjourn

In-Situ, Non-Destructive, 3D Neutron Imaging of Lithium Plating Following Extreme Fast-Charging of Full-Cell Lithium-Ion Batteries

Maha Yusuf [1], **Anders Kaestner**[2], **Yuxuan Zhang**[3], **Markus Wied**[4], **Jean-Christophe Bilheux**[5], **Nghia T. V**[6], **Markus Strobl**[7], **Vanessa Wood**[8], **Michael F. Toney**[9], **Johanna Nelson Weker**[10]

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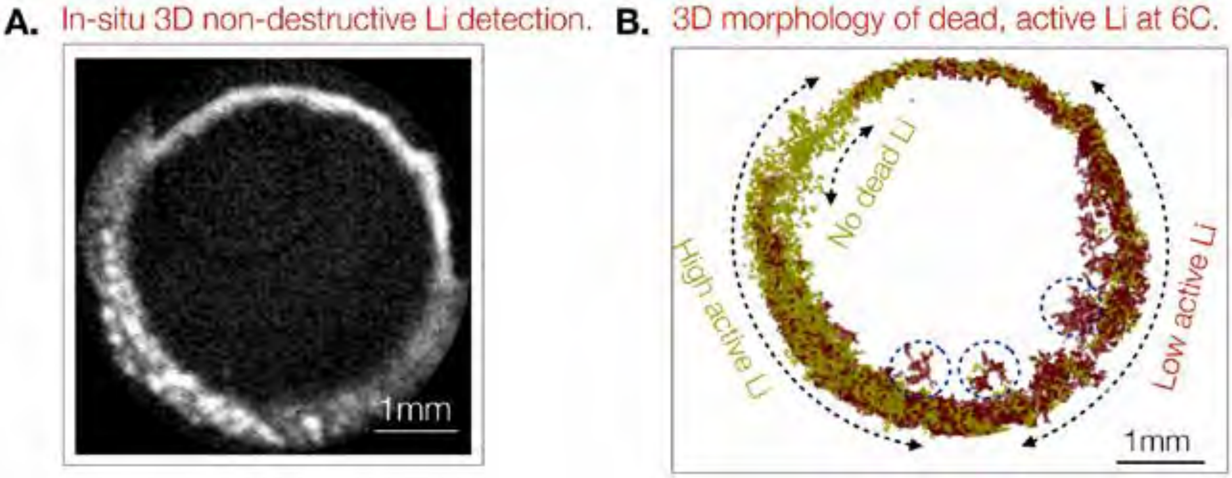
A primary challenge impeding extreme fast-charging (XFC) of current lithium-ion batteries (LIBs) for electric vehicles (EVs) within 10-15 minutes is the deposition of Li metal on graphite known as Li plating. After Li plates, it either re-intercalates into graphite to form active Li or becomes electronically disconnected forming dead Li. Previous studies have indicated that dead Li is the main contributor to the XFC-related capacity loss of LIBs. However, mechanistic understanding of the 3D morphologies and spatial heterogeneities of dead Li, and how they differ from those of plated and active Li following XFC remain unknown. Furthermore, link between 3D morphological evolution of dead Li and battery capacity fade following extended XFC cycling need to be investigated.

Here, we present an in-situ, non-destructive 3D characterization of the morphological behavior and spatial heterogeneities of plated, dead, and active Li on graphite electrodes in full-cell LIBs at 1C and 6C, using high-resolution neutron micro-computed tomography (μ-CT). In addition, we show 3D morphological evolution of dead Li on graphite following extended XFC (6C) cycling cycle numbers 10, 25, 50 and 150. We performed neutron μ-CT at two facilities: (1) Swiss Spallation Neutron Source at Paul Scherrer Institut (PSI), and (2) High Flux Isotope Reactor at Oak Ridge National Laboratory (ORNL). At PSI, we achieved a pixel size of ~ 5.74 μm and an effective spatial resolution of ~10-15 μm at ICON beamline. At ORNL, we achieved a pixel size of ~ 8 μm and an effective spatial resolution of ~25-30 μm at MARS beamline.

Our results reveal 3D spatial heterogeneities in the formation of plated, dead, and active Li at both 1C and 6C. We discuss these heterogeneities at four regions: (1) near the Cu current collector (CC), (2) middle of graphite, (3) graphite-separator interface, and (4) in the separator. Specifically, we found that Li near the Cu CC remains active whereas Li near the graphite-separator interface and in the separator becomes dead at both 1C and 6C. Additionally, we uncover distinct 3D morphology of plated and dead Li at 1C vs. 6C. Particularly, tip-like Li deposits were observed at 6C that were absent at 1C, suggesting a correlation between higher XFC-charging rate and cycling number and the formation of tip-like Li deposits.

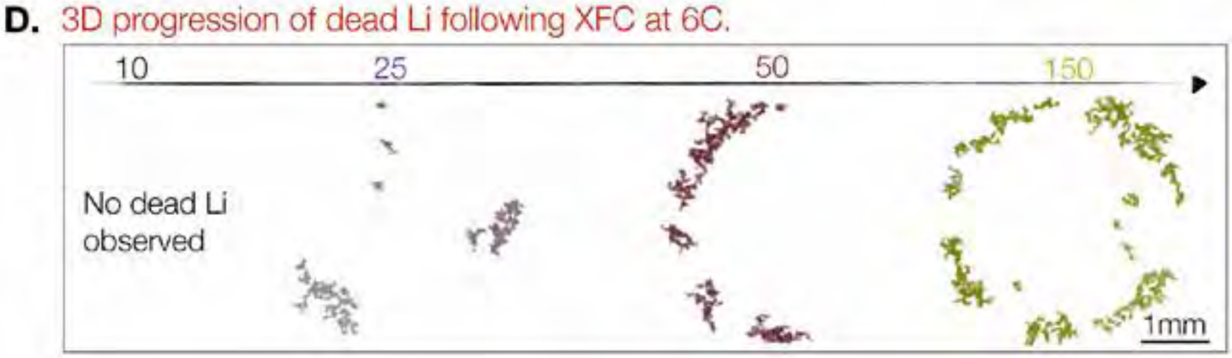
Additionally, we uncover 3D evolution of dead Li morphology from isolated plated deposits on only one edge of graphite after 25 cycles at 6C, to covering the entire circumference of graphite after 150 cycles. We also determined quantitative relationships between the amount of dead Li in 3D, XFC cycle number, and XFC-related capacity fade.

Finally, these results advance our mechanistic understanding of: (1) where Li plates, becomes dead, and remains active on graphite in 3D in full-cell LIBs during XFC, and (2) how dead Li progresses in 3D on graphite following extended XFC cycling at 6C.



A. In-situ 3D non-destructive Li detection. **B.** 3D morphology of dead, active Li at 6C.

C. 3D spatial heterogeneities of plated, dead, and active Li at 6C.



D. 3D progression of dead Li following XFC at 6C.

Tomographic Study of Rhizobox Dynamics

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Soil-root interactions are often studied using neutron imaging. The sample geometry is quite restrictive thanks to the high water-content in these systems. Two particular basic sample shapes used depending on the objectives of the investigation and the imaging mode. These are cylinders with a diameter which is mostly less than 25mm and slabs which are thin in the beam direction and wide in the image plane, figure 1a. The cylinder naturally ideal for tomography while the slab is more suited for radiography. The cylinders can only host very young plants before the root system reaches the cylinder wall. The slabs allow larger plants as the roots can grow naturally at least in the imaging plane. They are still constrained in the beam direction. As the models have become more refined there is a wish to determine the root position in the beam direction. This would again require a tomography, but the sample geometry does not allow it directly. Rudolph et al proposed to use laminography to solve this limitation [1]. This approach has some short comings that we address in this work; the feasibility of time series studies is limited and care must be taken to avoid relocation of the soil. Our approach is using a method called tomosynthesis or tilt series. A tilt series means that the acquisition axis is upright in the same manner as in a usual tomography scan. Only, the scan range is limited to a fraction of the 180° needed for a complete scan, figure 1b. The cost is naturally artefacts in the reconstructed images, just like laminography also has. The benefits are however; the sample never has to be dismounted during a time series radiography scan, i.e., it is easier to work with connected infrastructure. The sample does not need any specific stabilization to allow the tomography scan. It is possible to interleave radiography time series with tomography timeseries using the golden ratio scanning strategy [2]. We show the first results from ICON [3] demonstrating an interleaved radiography and tomography timeseries of a rhizobox, figure 1c.

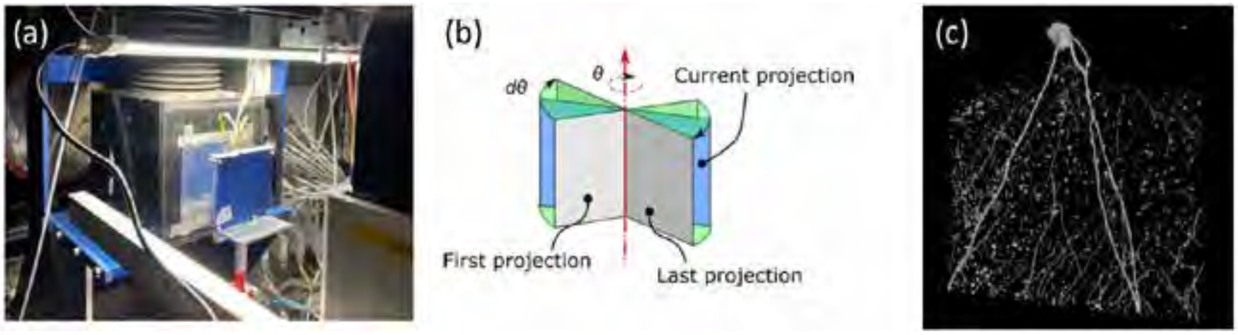

Figure 1: A picture of the setup (a). Tilt series scan arc schematic (b). The reconstructed roots in the slab (c).

[1] N. Rudolph-Mohr, S. Bereswill, C. Tötzke, N. Kardjilov, and S. E. Oswald, “Neutron computed laminography yields 3D root system architecture and complements investigations of spatiotemporal rhizosphere patterns”, doi: 10.1007/s11104-021-05120-7.

[2] A. Kaestner, B. Münch, P. Trtlk, and L. Butler, “Spatiotemporal computed tomography of dynamic processes,” *Optical Engineering*, vol. 50, no. 12, 2011, doi: 10.1117/1.3660298.

[3] A. P. Kaestner et al., “The ICON beamline A facility for cold neutron imaging at SINQ,” *Nucl Instrum Methods Phys Res A*, vol. 659, no. 1, 2011, doi: 10.1016/j.nima.2011.08.022.

White Beam Polarized Neutron Imaging of Weak Ion Currents in Energy Devices Via Induced Magnetic Fields

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Søren Schmidt[2], Alessandro Tengattini[3], Lukas Helfen[3],
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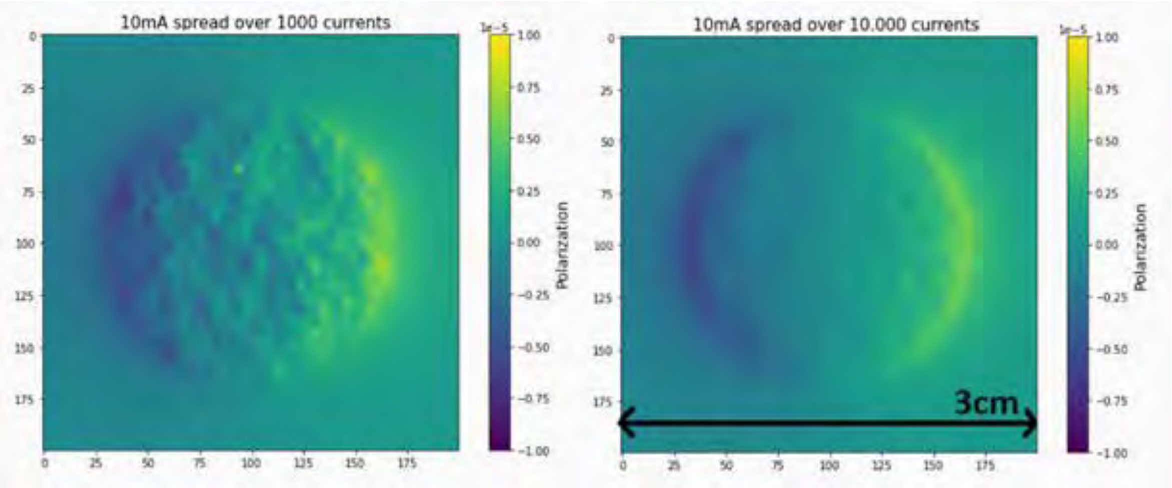
This study aims to investigate the ion current flow in energy devices by imaging their induced magnetic field. This is performed with polarized neutron imaging (PNI)[1], a technique capable of measuring the integrated magnetic field value across the neutron's flightpath, thereby granting spatial information on the ion currents inside the device, as well as a measurement of their strength.

By comparing pristine and degraded batteries we observe how sample damage such as dendrites affect the current flow, altering the homogenous magnetic signal that a perfectly even current flow would produce, into a signal with strong local fields surrounding local high current regions related to the dendrites.

The figure shows a simulation of the magnetic contrast as measured with PNI of a homogenously distributed 10mA current, and one limited to fewer current paths which is theorized to be the case when dendrites appear. Such simulations are compared to the experimentally determined magnetic contrast, to assist in determining the structure of the ion current flow inside the battery.



These experiments were conducted at the ILL NEXT[2] beamline wherein both custom built sodium-ion batteries and commercial Li-ion batteries were investigated, both cycled for an areal capacity of 25mAh/cm^2.

This presentation will discuss the field of polarized neutron imaging and the novel techniques applied to reach the necessary magnetic sensitivity required to image the vanishing magnetic signal of 10-10 T*m from a 10mA battery. These techniques include the usage of a white beam and transverse polarization measurements for maximal flux and sensitivity. It will also showcase the experimental data and subsequent analysis thereof, discussing the conclusions drawn from the study with regards to current flow behavior in batteries.

[1] Kardjilov, N., Hilger, A., Manke, I., Strobl, M., & Banhart, J. (2018). Imaging with polarized neutrons. In Journal of Imaging (Vol. 4, Issue 1). MDPI Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/jimaging4010023

[2] Tengattini, A., Lenoir, N., AndÃ², E., Giroud, B., Atkins, D., Beaucour, J., & Viggiani, G. (2020). NeXT-Grenoble, the Neutron and X-ray tomograph in Grenoble. Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 968. https://doi.org/10.1016/j.nima.2020.163939

Visualization of Liquid Water Behavior in a Polymer Electrolyte Fuel Cell Under High-Temperature Operation Using a Neutron Radiography

Yuto Obayashi presenting for Hideki Murakawa

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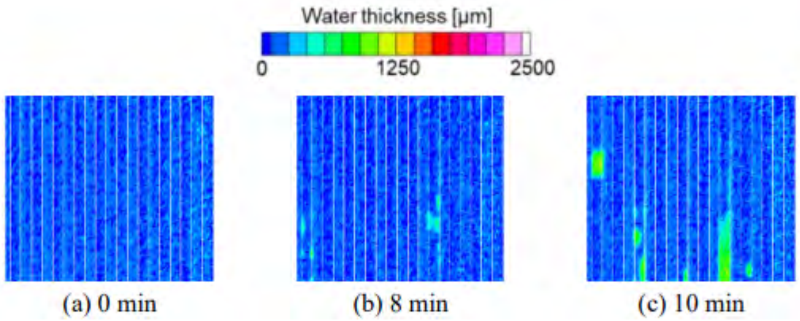
Water management in a polymer electrolyte fuel cell (PEFC) is a key topic for PEFC operation. Recently, there has been a demand for operating the PEFCs at more than 100°C to improve the power generation efficiency and the cooling performance of large fuel cell cars. Under these conditions, back pressure conditions are also crucial as operating conditions to maintain the proton exchange membrane (PEM) at an appropriate humidity. However, there are few investigations for evaluating the water distributions inside the PEFC under the operation at more than 100°C. In this study, a neutron radiography was employed for measuring two-dimensional water distributions during the PEFC operation. The neutron radiography facility at the B4 port in the Kyoto University Research Reactor (KUR) was used for the radiography. The visualization fuel cell has 10 straight channels with a width and a depth of 1 mm. The power generation area is 2 × 2 cm^2. The operation temperature was 105°C and the back pressure was set at 250 kPa_G. Water accumulation in the channel was confirmed as shown in the figure at 8 min after setting the current density to 1 A/cm^2 . It was also confirmed that the cell voltage fluctuated as the water accumulated.



(a) 0 min
(b) 8 min
(c) 10 min

Figure 1. Two-dimensional water distribution during the PEFC operation.

TRIXIE – Development and Construction of a New Neutron Imaging Instrument in the Czech Republic

Jana Matoušková[1], Lubomir Sklenka[1], Burkhard Schillinger[2], Nikolay Kardjilov[3]

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The Czech Technical University in Prague is currently building a new neutron imaging instrument named TRIXIE at the research reactor LVR-15. The LVR-15 is a 10 MW reactor located in Rez, near Prague, in the Czech Republic. The TRIXIE project started in the spring of 2022, establishing a conceptual design of the major components. This is the result of a collaboration between Czech Technical University in Prague, Helmholtz-Zentrum Berlin and Heinz Maier-Leibnitz Zentrum (FRM II). The TRIXIE instrument is intended for thermal neutron radiography and tomography techniques. This instrument comprises components such as fast neutron and gamma filters, a beam collimator with an aperture for thermal neutrons and primary and secondary shutters. The experimental area is a large shielding structure with a detection system, sample positioning tables and other equipment placed approximately 5 m away from the source. The TRIXIE instrument is expected to be completed by spring/summer 2024, and it will provide access to national and international user communities in various research disciplines. This should help to fill the gap between high users' requests and insufficient capabilities, which existing neutron imaging instruments provide nowadays in Europe.

The presentation will describe the instrument's general layout, explain the choice of the filters and collimators, and specify instrument capabilities. It also provides the status of the construction project with installed components.

A New Thermal Neutron Imaging Instrument at the Institut Laue Langevin

Andreas Meyer, Charles Dewhurst, Anna Fedrigo, Lukas Helfen, Alessandro Tengattini, Institut Laue Langevin
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Following the successful realization of the NeXT cold neutron and X-ray imaging instrument within the ENDURANCE program, the ILL pursues the realization of a new thermal neutron imaging instrument on a dedicated beamtube on the ILL reactor. This imaging instrument will be designed to tackle crucial engineering and societal challenges, which will take full advantage of the unique high-penetration capabilities of thermal neutrons to investigate real-scale samples, with applications on industrial components, but also large historical artifacts and paleontological specimens, as well as examinations of materials under extreme conditions. The new imaging instrument will provide a high neutron flux on sample that represents a significant increase with respect to NeXT at analogous collimation ratios, which further pushes increased spatiotemporal resolution.

In this presentation the layout of the instrument, expected performance as well as its science case will be discussed.

Final Design of Neutron Imaging System "NERA" at the Maamora Reactor

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A new neutron imaging instrument will be built to support the area of neutron imaging research at the Maamora Triga Research Reactor. The instrument is designed for the research community and routine quality control for industrial applications (e.g. automotive, aircraft, mining). This neutron imaging setup will be combined with the prompt gamma-ray activation instrument, and both systems will be mounted on the tangential channel. The thermal neutrons flux on the imaging plane is $6{\times}10^5$ n/m^2/s at a nominal L/D ratio of 300 and can be set for a range of 240-430.

The facility can operate with several beam sizes over a range of 80 mm - 240 mm square at 5.5m - 6m downstream of the L/D exchanger pinhole collimator entrance. This paper provides a technical description of the facility designed according to the state-of-the-art neutron radiography and tomography.

Experiments and Numerical Simulations on Fast Neutron Imaging

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Advanced Fusion Neutron Source (A-FNS) is an ongoing project to build a new neutron source to evaluate irradiation damage for nuclear fusion reactors. It will generate high intensity and high energy neutrons with a peak at 14 MeV through D-Li stripping reaction. As well as irradiation damage evaluation, the A-FNS may have wide applicability to use the large amount of neutrons such as RI production and neutron imaging. Especially the neutron of A-FNS may be worthy enough to perform fast neutron imaging which is a useful method to investigate the inside of thick materials or components.

To investigate a capability/feasibility of neutron imaging in A-FNS, 14 MeV neutrons are required to conduct demonstrations of the fast neutron imaging. However, there is no facility which generates such high energy neutrons and enough intensity to perform neutron imaging in Japan. PHITS (Particle and Heavy Ion Transport code System) developed by JAEA is a powerful tool to simulate particle transport phenomena which may include fast/thermal neutron imaging. Thus, this study regarding fast neutron imaging was conducted using PHITS. As well as numerical simulations, this study demonstrated fast neutron imaging by using J-PARC MLF BL-22 RADEN to validate and to improve PHITS simulation performed. Fast neutron imaging was demonstrated by a CCD camera system with a PP/ZnS scintillator produced by RC TRITEC LTD. As a result of the demonstration, it was confirmed that the penetration depth in fast neutron imaging was sufficient to visualize thick materials (see Fig.1). It was confirmed that fast neutron imaging can visualize much thicker objects than thermal neutron imaging. The transmission characteristics obtained by PHITS simulation were compared with those obtained by the experiments in J-PARC, and those were mostly agreed (see Fig.2). Consequently, PHITS simulations for fast neutron imaging which simulated BL-22 in J-PARC performed in this study were roughly reproducible.

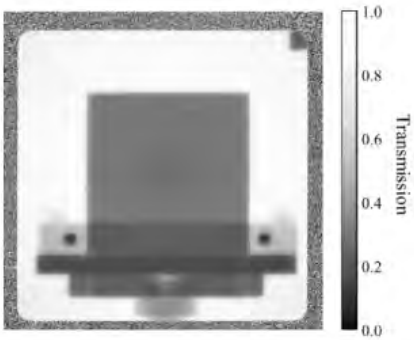

Figure 1. An example of experimentally obtained transmission image of steel (SS400) block (t = 3 cm)

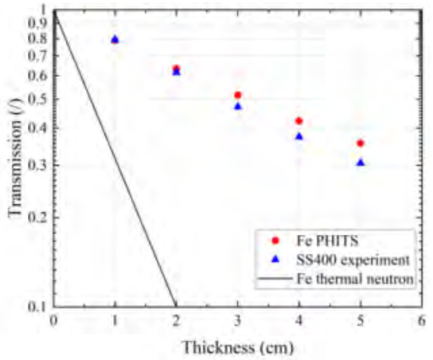

Fig.2 Comparison of iron transmission between numerical simulation and experiment

The Neutron Radiography at the Energy and Nuclear Research Institute/Brazil - IPEN: The Story so Far and Future Perspectives

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Neutron imaging (NI) has been an important and fruitful technique applied in the IEA-R1 reactor of the Energy and Nuclear Research Institute (IPEN) in Brazil during the last 30 years. Despite the limitations of the technology and the neutron flux provided by the 5 MW power reactor, the NI system is well-balanced in terms of pixel resolution (camera and scintillator screen), sharpness, and the neutron flux provided in each research reactor. In addition, the current NI system also enables researchers to perform a full sample reconstruction using the 3D tomography technique. This scenario has been allowing researchers to obtain relevant measurements in different areas, such as archaeology and industry, as well as researchers and student training. Even without considering this as a state-of-the-art instrument, the techniques and capabilities of the NI station possess great potential to develop research and be utilized by different stakeholders. Increasing the number of users could lead to the creation of new research projects and collaborations, potentially attracting funding from government agencies, for example.

It is imperative that the IEA-R1 NI system be constantly updated and improved in order to expand its capacities, collaborations, and user base. To address that demand, we have been studying the conversion of the tomography into a hybrid system through the installation of a Prompt-Gamma Activation Analysis (PGAA) apparatus. In this new system, the tomography apparatus used for rotating the sample will be utilized to access different sample positions, enabling both quantitative and qualitative analysis of chemical elements in the studied samples. In terms of safety and good instrument performance, it is mandatory to investigate the impact of these changes to ensure the image quality as well as the definition of the new apparatus components, e.g., collimator, detector, sample holder, etc., and its geometry. In this study, we investigate three different collimation systems by means of measurements and Monte Carlo simulations (MCNP). Besides, biological shielding is also analyzed through MCNP simulations. A ^{60}Co source has been used to analyze the performance of the shield structure of the collimators experimentally and connect the simulated scenarios with expected results on the NI station. Values are estimated through the comparison of results obtained by measuring the dose of the cobalt source without any collimation and the correspondent simulated scenario utilizing an MCNP code.

We have been able to determine appropriate geometry, shielding, and collimation for the hybrid system, and the results are promising. Therefore, the installation of the new instrument has already started, and the new shielding and collimator are being provided. After the installation, the commissioning process should start.

In short, the main scope of this work is to present the actual NI facility housed at the IEA-R1 reactor and also to describe the new PGAA system.

ODIN @ESS: Commissioning of the Instrument

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Virginia Martinez Monge[3], **Robin Woracek**[1], **Soeren Schimdt**[1],
Stefanos Athanasopoulos[1], **Alexandre Goncalves Gerk**[1], **Jan Hovind2**, **Markus Strobl**[2], **Michael Schulz**[3]

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The construction of the European Spallation Source (ESS) in Lund, Sweden, is currently underway, with beam operations expected to commence in 2025. Upon reaching this milestone, ODIN (Optical and Diffraction Imaging with Neutrons) will be poised to unveil its capabilities, initiating an 18-month commissioning and first science phase. As an advanced multipurpose imaging tool, ODIN boasts a series of 9 beam-shaping choppers (along with one T0 chopper) to facilitate tunable energy resolution and optimize flux according to experimental requirements. A roughly 45-meter ballistic guide transports the beam, allowing for bi-spectral extraction to enhance transmitted wavelength and broaden the range of applications.

The experimental area, or cave, is a substantial shielding structure providing ample space for demanding experiments, incorporating user-centric measures for experimenter convenience. Additionally, a flexible sample manipulation system has been designed to accommodate the most challenging experiments.

The majority of the installation is now complete, paving the way for the initiation of the first hands-on (cold) commissioning activities. This presentation aims to provide an overview of the current project status, highlighting the significant progress achieved and offering insights into the rationale behind the instrument's design choices. We will delve into the upcoming steps for instrument commissioning, outlining the timeline for achieving reliable operations and detailing the anticipated activities leading to early science at ESS.

Commissioning the VENUS Imaging Beamline at the Spallation Neutron Source

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The neutron imaging program at the Oak Ridge National Laboratory comprises capabilities at both the Spallation Neutron Source and the High Flux Isotope Reactor. At the reactor, the MARS imaging beamline provides a high flux of cold neutrons for increased contrast and highest spatial resolution on the order of 25 µm. Under construction at the Spallation Neutron Source since October 2018, VENUS is a time-of-flight neutron imaging beamline optimized to provide unique contrast capabilities with two techniques, Bragg edge and resonance imaging. Bragg edge imaging measures transmitted neutrons through crystalline materials. When the Bragg condition for diffraction is met (i.e., the neutron wavelength corresponds to twice the lattice spacing), there is an abrupt change in the transmission intensity, the so-called Bragg. While the height of the edge provides a means to quantify the amount of phase in a material, its position provides information about the strain for a given <hkl> plane. Resonance imaging is based on the absorption of neutrons with energies above 0.5 eV by nuclei in the sample. These attenuation peaks allow the 3-dimensional maps of elements and isotopes specifically.

The construction project is focused on the design, procurement, testing, and installation of the beamline equipment. In the next few months, the beamline cold commissioning without neutrons will consist of integrating equipment controls into a user-friendly interface. The hot commissioning with neutrons will start during summer 2024 (expected completion of the VENUS construction project) and will employ experiments that characterize the performance of the source, the instrument, and demonstrate its suite of capabilities.

The presentation will show a general layout of the beamline, its key capabilities and equipment, and an overview of the commissioning plan, including the initial workflows available at the beamline.

Photograph of the VENUS beamline showing from left to right the cave, beam stop and control hutch.

This research used resources at the Spallation Neutron Source, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.

Construction of the VENUS Imaging Instrument at the Spallation Neutron Source: The Engineer's Perspective

R. Aaron Hanks[1], Hassina Z. Bilheux[2], Amy Byrd[3], Amy Jones[1], Mark Lyttle[1], Ian Turnbull[1], Matthew Balafas[1], David Conner[1], Bill Mchargue[1], Steven Mellard[1], Matt Kyte[1], Elias Pulliam[1], Paris Cornwell[1], Ryan Mangus[1], Timothy Lessard[1], Justin Bolton[1], Stephanie Jolley[1], Harley Skorpenske[2], Jamie J. Molaison[2]

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The construction of a neutron scattering or imaging instrument at a functioning neutron facility is often challenging due to the duration of the project, the coordination between the neutron production days and the installation at the beamline, and the overall complexity of the beamline components. The VENUS construction project started in October 2018. After the design phase, installation of major components such as with the beamline shutter, core vessel insert, and shielding started late 2019. The global pandemic impacted the project in terms of cost and schedule. The VENUS beamline can be divided in three main sections: the front-end optics, the cave and beam stop, the radiological materials area and control hutch. The front-end is where optical components such as the fixed aperture, the variable aperture system, and collimators are positioned. The chopper suite composed of two bandwidth choppers and one T_0 chopper is also located in the front-end section of the instrument, along with the cadmium filter used to remove thermal and cold neutrons when performing resonance imaging with a field-of-view of 4 x 4 cm^2. Bragg edge imaging can be performed with a field-of-view of 20 x 20 cm^2. Other modes such as thermal/cold or epithermal white beam are also available at VENUS. The cave is equipped with the sample slit system, the sample positioning table, and the detectors. The radiological materials area is dedicated to experimental testing prior to neutron beam time. It is also the area where future components such as detectors will be tested. Flight tubes are installed throughout the beamline path to limit air scattering.

The presentation will focus on the challenges encountered at the different phases of the project, i.e., design, fabrication, testing, and installation challenges and how our engineering team developed creative solutions to overcome them.

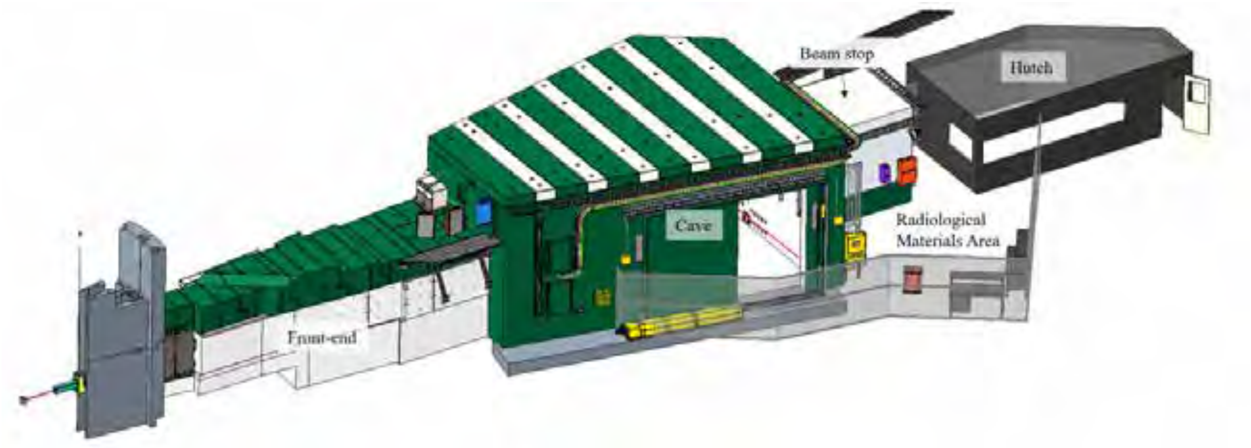

Figure 1: VENUS Instrument Model Rendering

This research used resources at the Spallation Neutron Source, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.

Data Workflow and So-Ware Tools at VENUS

Jean-Christophe Bilheux, Hassina Bilheux, Anton Khaplanov,
Matthew J. Bedynek, Rob Knudson IV,
Greg Guyotte, Chen Zhang, Kaz Gofron, Zach Thurman,
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The cutting-edge TOF imaging beamline VENUS at the Spallation Neutron Source of the Oak Ridge National Laboratory starts commissioning summer 2024. Thanks to the experience acquired at the SNAP and MARS beamlines, we have designed various analysis tools and a new intuitive data acquisition system user interface. VENUS will begin commissioning with the micro-channel plate (MCP) Timepix detector and light sensitive cameras that include charge-coupled device and complementary metal oxide semiconductor sensors. An MCP Timepix3 detector is scheduled to commission concurrently with the VENUS commissioning and will be available for the general user program at the beamline. Since this new detector acquires data in event mode, the hardware and data workflow require careful planning described in this presentation. A new version of the in-house Imaging Bragg Edge Analysis Tools for Engineering Structures (iBeatles) has been produced thanks to the feedback received at the 11th workshop on neutron wavelength-dependent imaging held in Japan in 2023. This presentation gives an overview of the VENUS hardware and software infrastructures, the data workflow, the VENUS data acquisition interface and features available in the new version of iBeatles.

This research used resources at the Spallation Neutron Source, DOE Office of Science User Facilities operated by the Oak Ridge National Laboratory. The team would like to thank the user community for their many contributions in guiding the development of the software tools as well as being gracious with their time when testing the notebooks.

Overview of Science Capabilities of VENUS Beamline

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The newly constructed energy resolved neutron imaging beamline at ORNL will support a broad range of experimental studies in areas as diverse as materials science, energy research, additive manufacturing, cultural heritage, geology, electrochemistry and many others. In addition to white beam radiography and tomography the possibility to measure neutron transmission spectrum in each pixel of the image data set substantially extends the range of sample characteristics which can be extracted from a single experiment. Both neutron attenuation and diffraction, as well as resonance absorption contribute to the contrast in the resulting imaging data set consisting of thousands of images, each corresponding to a narrow energy range, spanning many orders of magnitude from epithermal to cold neutrons, all obtained in one experiment.

In this talk we will discuss what studies can be performed at VENUS beamline based on the results obtained previously at SNAP beamline at ORNL and other beamline facilities around the world. The dedicated imaging beamline at the Spallation Neutron Source at ORNL will be a great addition to only few existing facilities in the world and it will support the development and optimization of many unique and exciting experimental methods.

The Future CUPI²D Beamline at the STS: A General Update Including Optics Design

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CUPI²D (Complex, Unique and Powerful Imaging Instrument for Dynamics) is one of eight instruments selected to be built within the Second Target Station project (STS) at the Spallation Neutron Source, Oak Ridge National Laboratory. The beamline is being designed as a truly dynamic imaging instrument capable of capturing phenomena within seconds to minutes. The high cold flux and brightness of the STS will allow for simultaneous computed tomography (CT), Bragg edge imaging, (BEI) and neutron grating interferometry (nGI) measurements, capturing spatially discriminated data across ten spatial orders of magnitude. Since CUPI²D is designed to produce intuitive multiscale data from day one and will serve a very broad audience many of whom are outside of the academic domain of neutron scattering the integration of its systems and lessons learned from the IMAT, RADEN, ODIN, and VENUS instruments will be pivotal. We will outline the technological and design advancements spearheaded by the CUPI²D instrument team in conjunction with the STS engineering group over the last two years. A particular focus will be given to advancements in the beamlines optics and cave design. We conclude with an opportunity for the imaging community to contribute to the design process by establishing a standing working group that advocates for CUPI²D during its evolution. This research used resources of the Spallation Neutron Source Second Target Station Project at Oak Ridge National Laboratory (ORNL).

In-Situ Neutron Radiography with Hydrogenated Tensile Samples in the INCHAMEL Facility

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Nuclear fuel rods consist of fuel pellets inside of cladding tubes. In Light Water Reactors (LWR), cladding tubes made of zirconium alloys are in direct contact to the surrounding cooling water. Thus, they undergo an oxidation process where a certain fraction of the produced hydrogen may penetrate into the cladding and precipitate as hydride in the metallic matrix. An applied tensile force in the elastic range increases the hydrogen solubility and diffusivity and thus may initialise a re-orientation process of hydrides that could be destructive for the metal. During long-term dry storage conditions, the stress influence in the elastic range on the zirconium claddings seems to be relevant, but not quantified yet.

This paper presents in-situ neutron radiography experiments of hydrogenated zirconium tensile samples under the influence of different elastic tensile stresses. The experiments at the ICON beamline at the PSI were conducted during the commissioning of the INCHAMEL (In-situ Neutron radiography CHAmber for tests under MEchanical Load) facility (Fig.1), a tensile testing machine with a conductive heating system. The stress influence on hydrogen movements in the elastic range for short time frames (hours) was shown to be negligible. Only under the influence of plastic tensile stresses, hydrogen movements from regions with lower to higher stress were observed. Nevertheless, the first results show that the INCHAMEL facility can be successfully used for investigations of elastic stresses on the hydrogen diffusion and solubility in zirconium. However, the duration of the experiments and/or the resolution during the neutron imaging have to be optimised.

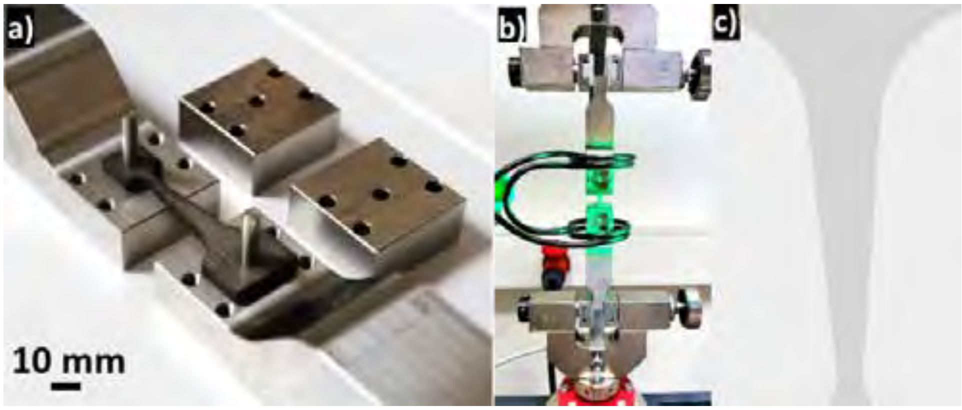

Figure 1. Tensile sample with sample holder (a), placed in the INCHAMEL facility (b) and measured with neutron radiography (c) at the ICON beamline of the Paul Scherrer Institute in Villigen, Switzerland.

Post Ramp and LOCA Simulation Characterization of Cr-Coated Zircaloy-4

Aaron W. Colldeweih[1], Aaron Craft[1], David W. Kamerman[1], Malachi Nelson[1], Nathan Capps[2], Caleb Massey[2], Mackenzie Ridley[2], Michael Meyer[3], Okan Yetik[3], Pavel Trtik[3]

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The development of accident tolerant fuel (ATF) concepts began as a result of the Fukushima nuclear accident in Japan. The primary objective of ATF cladding is to enhance the cladding corrosion resistance. The most prominent ATF cladding candidate is a chromium coated zirconium alloy. The material in this work involves a PVD Cr-coated Zircaloy-4 cladding. The test matrix included three sets of tubes that were all internally pressurized at elevated temperature (300°C) to simulate in-reactor ramping conditions. The pressurization induced biaxial loading conditions, namely high hoop strain in addition to axial strain. The second and third set of tubes were additionally subjected to high temperature, and high purity hydrogen environments to simulate an accelerated hydrogen pickup through potential flaws in the Cr-coating. The third set of tubes was then tested at the severe accident test statin (SATS) at Oak Ridge National Laboratory (ORNL) where the tube was pressurized and heated a rapid rate until bursting. Each set of tubes were then sectioned to 4.0 mm lengths and imaged along the axial direction of the tube using the Neutron Microscope (NM) at the ICON beamline at the Paul Scherrer Institute (PSI). Radiography results show the effectiveness of even a severely strained Cr-coating at preventing hydrogen uptake. Radiography also provides insight into the differences in deformation that takes place in the pre-strained versus as-received Cr-coating near the opening of a burst tube. These results highlight the capabilities and challenges of radiography for materials with thin coatings using for the first-time high-resolution neutron radiography on ATF cladding.

The Fuel Motion Monitoring System at TREAT - Current Status and Future Plans

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An important component of the United States Nuclear Fuel Safety Transient Testing Program, the Fuel Motion Monitoring System (FMMS) at Idaho National Laboratory's Transient Reactor Test Facility (TREAT) is fast-neutron hodoscope capable of imaging the location, movement, and relocation of nuclear fuel experiments under simulated transient accident conditions. The FMMS was refurbished in parallel with the TREAT restart program starting in 2014, restoring 96-channels of fast-neutron detection. Since returning to operation in 2017 the FMMS has supported many fuel safety experiments supporting accident tolerant fuel development, light-water reactor safety, space thermal nuclear propulsion fuel development, and advanced reactor research and development. In Phase 2 of the FMMS restoration, work is now under way to expand the FMMS' field-of-view by adding an additional 96 channels of fast neutron detectors to the system's hodoscope, along with an expanded data acquisition system and associated transient timing electronics. An overview of the FMMS system and its fast-neutron detectors will be presented along with examples of current FMMS imaging performance and associated information.

Spatially Resolved Texture Characterization Of Cold-Rolled Zircaloy-4 Cladding by Bragg Edge Imaging

Pavel Trtik presenting for Florenciz Malamud

Florencia Malamud[1], **M.A. Vicente Alvarez**[2], **V. Stella**[2], **J. Santisteban**[2], **G.Juarez**[2], **M. Strobl**[1]

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Zircaloy-4 is widely used in the nuclear industry to fabricate fuel cladding tubes for nuclear reactors. The processing schedule of these tubes involves a sequence of 3-4 cold rolling steps with intermediate recrystallization thermal treatments.

The texture evolution during the first rolling step, involving a total reduction of ring area of approximately 80% was characterized by neutron diffraction. This was done at Kowari instrument of ANSTO after the extraction of probes at selected points of the cold-deformed tube. The results displayed texture gradients across the tube radial direction, associated mainly with the distribution of the c-poles of the hexagonal structure along the radial-hoop plane, while the (11-20) poles point along the axial direction for both inner and outer regions of the tubes. As deformation proceeds there is a 30° rotation of the grains around the c-axis and after 30% plastic deformation the (10-10) poles end pointing along the axial direction of the tube. The observed gradients are a consequence not only of inhomogeneities in the original material but also of differences in the strain history of the different regions of the tube introduced during the pilgering cold rolling process.

Bragg edge imaging experiments were carried out at the BOA beamline of the Paul Scherrer Institute on ring-shaped specimens cut at different axial positions of an unfinished, partially deformed, tube, to characterize the spatial variation of the crystallographic texture along the section of these rings, each corresponding to a different degree of plastic deformation. Maps of the (10-10) and (11-20) Bragg edge heights were constructed, as indicative of the 30° rotation around the c-axis due to deformation. The results were consistent with the neutron diffraction data, showing that the initial texture is dominated by the <100> fiber and during deformation the <110> fiber became increasingly important at the expense of the <100> fiber. To exploit the information provided by the full Bragg edge spectra, a more sophisticated data processing method was developed. This method is based on the assumption that the texture can be reduced to two fibers with varying volume fractions. These fibers have either their <100> or <110> directions parallel to the axial direction of the tube. For each ring, the volume fraction of the fibers was refined from the transmission data employing a recently developed attenuation coefficient model for fiber-textured materials. The results obtained were consistent with the Bragg edge height analysis.

Observation of Nano-Void Coalescence in Hydrogen-Fatigued Vessel Steel Using Neutron Dark Field Imaging

Dan Hussey presenting for Youngju Kim

Youngju Kim[1], Daniel S. Hussey[2], M. Cyrus Daugherty[2], Caitlyn M. Wolf[2], Pushkar Sathe[2], Paul A Kienzle[2], Jacob M. LaManna[2], David L. Jacobson[2], Katie M. Weigandt[2], Peter N. Bajcsy[2], Sarah M. Robinson[2], Nikolai N. Klimov[2], Ryan P. Murphy[2], Michael G. Huber[2], Yuxuan Zhang[3], Hassina Bilheux[3], Jongyul Kim[4], Taejoo Kim[4], Zachary N. Buck[2], Matthew J. Connolly[2]

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Hydrogen embrittlement (HE) presents a significant risk to engineering structural materials, leading to cracking or failure at stress levels below the yield stress. The Nano-Void Coalescence (NVC) model is one of the mechanisms of HE. This model suggests that hydrogen-enhanced localized plasticity increases the formation of vacancies. These vacancies then coalesce, forming voids several tens of nanometers in size, resulting in material failure.

Neutron grating interferometry is a valuable technique for providing information about microstructures within bulk objects. This method utilizes dark field (DF) contrast, which arises from small-angle neutron scattering. The DF contrast varies with the autocorrelation length, which is proportional to the product of the neutron wavelength and the sample-detector distance, divided by the period of the Moir-fringe. By measuring DF contrasts at many autocorrelation lengths, it is possible to probe the pair correlation function and assess structural parameters of microstructures, such as voids size and concentration.

In this study, we investigate the NVC in hydrogen-fatigued vessel steels using neutron DF imaging. The steel post samples were subjected to fully reversed strain-controlled loading until failure, across a range of applied strain amplitudes, in both air and hydrogen environments. Neutron imaging experiments were conducted at the Multimodal Advanced Radiography Station (MARS) at the CG1D beamline of the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) and the Ex-core Neutron Irradiation Facility (ENF) at HANARO in the Korea Atomic Energy Research Institute (KAERI). Through DF imaging, we can obtain spatially resolved structural information on NVC and demonstrate the correlation between strain amplitude and void microstructure. This contributes to a further understanding of the NVC model of hydrogen-assisted failure.

Pulsed Neutron Characterization of Irradiated Fuels at Lansce

Sven C. Vogel[1], J.R. Angell[2], T. Balke[1,3], C.A. Bouman[3], L. Capriotti[2], A.E. Craft[2], B. Gross[2], J. Harp[1], P. Hosemann[4], A.M. Long[1], E.J. Larson[1], K.J. McClellan[1], Vedant Mehta[1], B. E. Wohlberg[1]

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Neutrons offer bulk, non-destructive characterization of irradiated materials for which other bulk methods, e.g., X-ray tomography, are not suitable due to the immense gamma background emitted from the samples. In particular, pulsed neutrons provide information from the ability to resolve the neutron energy using their time-of-flight. This enables the potential to utilize neutron absorption resonance to characterize the spatial distribution of isotopes. As was demonstrated previously, neutron resonance spectroscopy may allow to characterize the distribution of fission and neutron capture products non-destructively. Besides neutron resonance-based radiography and tomography, neutron diffraction provides information on the microstructure (texture, crystallographic phases and their phase fractions). Both of these techniques may ultimately be applied to the bulk of an irradiation capsule prior to destructive post-irradiation examination to identify regions of interest. Characterization of the entire irradiated sample volume with these techniques will ultimately identify normal and abnormal regions within the entire irradiated volume, guiding destructive evaluation and thus maximizing insight from expensive irradiation campaigns. As a step towards this goal, an Advanced Test Reactor irradiated U-10Zr-1Pd sample was characterized with an NSUF funded rapid turnaround experiment. U-10Zr metallic fuels are researched as host materials for potential transmutation fuels and the addition of palladium strives to bind lanthanides, thus preventing fuel cladding chemical interactions (FCCI). This is the first pulsed neutron characterization of an irradiated fuel at LANSCE. The SHERMAN cask (Sample Handling Environment for Radioactive Materials Analysis using Neutrons), designed to enable characterization of samples up to 900 R/hr dose rates, will also be presented.

WCNR 12

PRESENTATION ABSTRACTS
THURSDAY, 6 JUNE 2024

THURSDAY, 06 JUNE 2024

Pre-session

8:00	Welcome & Announcements

Cultural Heritage | Chair: Ulf Garbe

8:10	**Eberhard Lehmann** | How To Perform Cultural Heritage Research by Using Neutron Imaging?
8:30	**Tushar Roy** | Characterization of Ancient Indian Archaeological Artefacts Using Neutron Imaging
8:50	**Ocson Cocen** | Insights From Neutron and X-Ray Computed Tomography Analysis on Archaeological Nails From Bois De Châtel, Avenches, Switzerland
9:10	**Joseph Bevitt** | The Invisible Revealed: Cultural Forensics with Neutrons at the Powerhouse Museum
9:30	Break

Detectors | Chair: Yasushi Saito

9:45	**William Chuirazzi** | Boron-Based Neutron Scintillator Screen Characterization with X-Rays and Neutrons
10:05	**Bernhard Walfort** | Scintillation Screens for Neutron Imaging
10:25	**Jarek Glodo** | Low-Cost Scintillator Composites for Thermal Neutron Imaging
10:45	Break

Neutron Grating Interferometry / Dark Field Imaging | Chair: Markus Strobl

11:00	**Camilla Buhl Larsen** | Orientation-Dependent Grain Level 3D Strain Evolution in Oligocrystalline CoNiGa
11:20	**Simon Sebold** | Shape and Size Distribution of the Magnetic Domain Structure in Electrical Steel Measured with Neutron Grating Interferometry
11:40	**Alex Backs** | Observation of the Macroscopic Magnetic Domains in Silicon Steel During Magnetization with Polarized Neutron Imaging
12:00	**Alaleh Aminzadeh** | Neutron Diffusive Dark-Field Imaging Using a Structured Mask
12:20	Day 4: Working Lunch: Neutron Grating Interferometry Discussion led by Hassina Bilheux **2nd Board Meeting with New Board Members (Exec. Conf. Room)**

Neutron Optics | Chair: Alessandro Tengattini

14:00	**Manoraj Dhanalakshmi Veeraraj** | Development of An Achromatic Neutron Lens
14:20	**Yasushi Saito** | Enhancement of Spatial Resolution in High-Speed Neutron Imaging Using a Multi-Slit Collimator
14:40	**Daniel Hussey** | Development Plans for the NIST Cold Neutron Imaging Instrument

Conclusions & Outlook

15:30	**Break**
16:00	**Travel To Conference Dinner**
17:00	**Conference Dinner at EBR-1**
19:30	**Travel To Hotel**

How to Perform Cultural Heritage Research by Using Neutron Imaging?

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The observation of inner, hidden material distributions of objects with cultural heritage importance requires methods which enable a certain transmission of the used radiation. Because light is limited for opaque samples, only X-rays and neutrons can be used for such investigations. Alternative kinds of radiation like electrons, micro-waves are limited in the practical transmission and the required spatial resolution.

Relevant samples of interest are stored mainly in museums round the globe, but also in private collections. The interest to perform non-invasive investigations of their objects is not identical for these two groups. In the case of museums, mostly government owned and strongly linked to scientific (archaeological) institutions, the results of a study should help to understand human history and manufacturing processes. Private collectors are more interested in the authenticity, age and finally the value of their objects.

Many studies on cultural heritage (CH) objects have been performed with X-rays, today also in tomography mode, if possible. Some museums have now own X-ray laboratories or a direct access to them.

However, there are many cases, in particular when large amounts of metals are involved, where this kind of radiation is limited. Here, neutrons have better chances for transmission. In addition, small amounts of organic materials can be observed by neutron imaging methods.

This paper will show several examples, where neutron imaging is applied successfully, while X-rays did fail. Based on the results, some guidelines can be given, when and under which conditions neutron imaging is applicable and preferred.

There are also cases, where the combination of both X-rays and neutrons can synergistically bring out the best result. Combining sources and detectors into one facility is the way to go, as demonstrated in the NEUTRA/XTRA facility at PSI [1].

Besides a retrospective of successful project, we want to present ways how to collaborate and to emphasize the importance of personal commitment and contact with relevant people in the museum's community. In order to continue with this type of investigation, it is of utter importance to get the power and performance of neutron methods needs to become more visible to the cultural heritage community. Often, the direct contact with the relevant persons has enabled successful studies. Data libraries of existing studies can help to overcome gaps and to understand each other.

Such a data library of results is under preparation for ancient Tibetan bronze objects, studied with neutron imaging methods at the PSI facilities. It should be made available for further studies and considerations by the Buddhist community and museums experts.

[1] E. Lehmann et al., doi.org/10.3390/app11093825

Characterization of Ancient Indian Archaeological Artefacts Using Neutron Imaging

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Neutron Imaging can provide useful information to characterize the structure, morphology and composition of cultural artefacts through a three-dimensional reconstruction of the sample under investigation. From these data it is possible to detect hidden features inside objects, to understand ancient manufacturing technology, to evaluate the conservation status and identify past restoration works and to characterize new conservation methods.

The present paper presents the investigation of archaeological metallic statuettes, ancient Indian coins and weapons. The experiments have been carried out at Neutron Imaging Beamline, Dhruva reactor, India. This paper utilizes a combination of neutron computed tomography and neutron diffraction analysis to demonstrate the efficacy of employing neutron-based methodologies for the purpose of investigating metallic statuettes, thereby shedding light on their structural and phase characteristics, all while obviating the need to physically dissect the sample. In order to corroborate the findings obtained from the neutron-based techniques, supplementary methodologies such as energy dispersive X-ray fluorescence were employed to extract elemental information and validate the results. By harnessing the power of both neutron and X-ray-based techniques in unison, we were able to discern concealed structural attributes within the 17th century metallic statuettes under investigation, as well as ascertain the precise phase composition of the brass alloy, thus further enriching our understanding of its manufacturing practices of brass statutes in the ancient era.

Insights from Neutron and X-Ray Computed Tomography Analysis on Archaeological Nails from Bois De Châtel, Avenches, Switzerland

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In archaeological heritage conservation and restoration, it is pivotal to assess the stability of excavated material to plan their handling and treatment properly. It is a challenging task for iron archaeological artifacts (IAA), as they are often very unstable and reactive due to the presence of active corrosion sites that are visually inaccessible. The degradation process may start when these objects are removed from the ground. Thus, there is a need to more accurately predict the corrosion state of IAA before excavation to enable proper measures to be taken. A truly nonintrusive and multimodal method that fuses neutron and X-ray computed tomography (NCT and XCT) [1] can gather artifacts' surface and bulk information with almost non-existent sample preparation. As known, matters interact unequally with neutrons and X-rays: neutrons are more sensitive to light elements, while heavier elements tend to interact more with X-rays. By exploiting neutrons' and X-rays' complementary characteristics, the CORINT project (corrosion-corint.ch) aims to elucidate iron corrosion phenomena within opaque, porous media like soil.

For the development and optimization of this multimodal technique, a few archaeological nails were excavated from the archaeological site of Bois de Châtel in the Avenches region (Switzerland) using a methodology developed to minimize disturbances to the burial state of these nails. The nails were then imaged at the cold neutron beamline of Paul Scherrer Institute, ICON, where NCT and XCT were performed. One of them, BdC 2, has been chosen as a case study for this talk, and extraction of corrosion and degradation features from the NCT and XCT images will be presented.

The nail is heavily mineralized; thick corrosion layers heterogeneously enwrap the nail. After analyzing the 3D reconstructed images, we distinguished the remaining metal core from layers of corrosion products, the existence of an air pocket in corrosion scales, and delaminated layers inside the nail bulk. The delaminated layers indicated that the nail was manufactured through multiple passes of forging and folding. This feature would most likely have been missed or lost using traditional conservation techniques, making this a prime example of how revolutionary this multimodal imaging technique is for archaeology. For results validation, several cross-sections of the BdC2 nail are cut and then analyzed using usual ex-situ, intrusive analyses, such as optical microscopy, Raman spectroscopy, and SEM-EDX. Thanks to the possibility of digitally slicing the 2D and 3D images, several regions of interest can be efficiently pinpointed instead of blindly physically cutting possibly interesting areas for further analysis.

[1] E. Granget, O. Cocen, et al., "Neutron and X-ray computer tomography for the study of undisturbed iron archaeological artifacts", SR2A– 10th international conference on synchrotron radiation and neutrons in art and archaeology, Munich, Nov 21-24, 2023.

The Invisible Revealed: Cultural Forensics with Neutrons

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The Powerhouse Museum in Sydney houses more than half a million objects of cultural significance, spanning more than 3000 years of human technological advancement. "The Invisible Revealed" exhibition (Nov 2021 - Sep 2022) showcased curatorial and conservational discoveries made through a partnership between Powerhouse and the Australian Nuclear Science and Technology Organisation (ANSTO). The Exhibition presented 26 of the Museum's objects alongside digital 3D models produced using innovative neutron- and synchrotron-X-ray tomography, photogrammetry, an interactive Digital Twin of ANSTO's DINGO neutron imaging facility, Artificial Intelligence, and other insights achieved with nuclear methods.

The Invisible Revealed brought together cross-disciplinary researchers from across ANSTO's nuclear capabilities, resulting is the first major museum research exhibition for ANSTO, and internationally, the first centre on neutron imaging as the showcase technology. The exhibition demonstrated the innovative application of neutron imaging and other methods to curatorial science, achieved unprecedented public engagement for an exhibition of its type, and was awarded the prestigious 2022 Australian Museums National Award for Innovation.

This talk provides an overview of neutron imaging applied to some of Australia's nationally significant objects in this award-winning exhibition, revealing the hidden mechanisms, repairs, degradation and insights gleaned in miniature spy cameras, a T'ang Dynasty statue, and how neutron imaging can be integrated with other nuclear methods to glean insights into the world's earliest coinage.

Boron-Based Neutron Scintillator Screen Characterization with X-Rays and Neutrons

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As neutron imaging becomes more utilized for nondestructive examination of samples ranging from concrete to aerospace components to nuclear fuel, optimization of neutron imaging systems is under way to improve neutron detection efficiency and data quality. A key component of the imaging system is the neutron scintillator screen, which directly affects the system's detection efficiency and achievable spatial resolution. Recent research has explored development of boron-based neutron scintillator screens, which potentially offer improved spatial resolution and detection efficiency, provided there is sufficient neutron flux, compared to traditionally employed lithium-based screens.

This work builds upon previous efforts to help improve boron-based neutron scintillators by combining neutron imaging data acquired with a newer generation of boron-based scintillator screen with micro X-ray computed tomography data of the screen itself, especially revealing grain sizes and shapes. This presentation describes a method for using X-rays to evaluate screens and screen fabrication characteristics and discusses advantages over traditional examination methods. The X-ray and neutron data is then used in tandem to quantify scintillator screen performance.

Additionally, scintillators fabricated using different combinations and approaches are examined and compared to one another. More recently developed boron-based scintillators are compared to previous iterations of such scintillators, as well as to the more commonly utilized lithium-based screens. This presentation concludes with an outlook on how nondestructive evaluation techniques can be adapted to inform the development of new, improved neutron scintillator screens and neutron converter materials.

Scintillation Screens for Neutron Imaging

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Neutron imaging detectors based on a very light-sensitive camera, which observes the emitted light from a scintillator screen have become a standard tool at many facilities. Meanwhile, there are systems available for very large field-of-view (FOV), very high spatial resolution[1], high frame rate[2] and those for sophisticated new methods. Each of them has specific requirements in particular related to the scintillator screen - one of the key components.

Started in 2005, we have developed until now several kinds of scintillation screens. The manufactured screens are exported all over the world. Now the costumer can choose between different neutron absorber materials, scintillation materials, their thickness, size and substrate.

With respect to the used neutron spectra, thermal and cold neutrons are most important and dominate in the applications. However, for larger objects and specific applications, also epi-thermal neutrons and fast neutrons have advantages. For these applications, another class of scintillators has had to be developed and introduced into practical use [3,4].

Because neutrons are uncharged particles, they do not induce ionization processes directly. Therefore, a primary nuclear reaction is needed to initiate countable events. In the thermal and epi-thermal spectral range, the capture of the neutrons by strong absorbers is the dominating conversation reaction. For Neutron Imaging with thermal neutrons two major lines of neutron sensitive scintillator materials have been established: The one with separate absorber material and scintillation material, the combination of 6LiF and ZnS or the one with the absorber inside of the scintillation material, Gadolinium oxysulfide, which is also used for X-ray imaging. Other possible absorbers are Dy, Hf, Eu and B[5] showing special features in non-standard applications.

We give an overview of tested absorber / scintillation material combinations and its advantages / disadvantages in the context of neutron imaging.

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Low-Cost Scintillator Composites for Thermal Neutron Imaging

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Neutron imaging serves as a pivotal tool across diverse scientific and industrial domains, notably in materials science, engineering, and medical diagnostics. However, current solutions encounter various challenges, including effective capturing and converting neutron radiation into detectable signals. Widely used materials such as ZnS(Ag)/LiF exhibit limited efficiency, LiI(Eu) is hygroscopic, and Gd-based scintillators, including GOS:Pr, present issues with conversion electrons as low-energy reaction products.

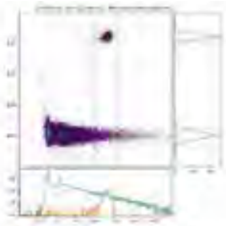
Addressing these challenges necessitates the exploration of novel scintillator materials or solutions designed to elevate the sensitivity, resolution, and overall performance of neutron imaging systems. One promising avenue involves the development of composites. An example of composite is a mixture of ZnS(Ag)/LiF phosphors, where ZnS serves as the emitter and LiF as the absorber. However, this configuration introduces limitations related to transparency. The opaque nature of powder screens, while enhancing detection efficiency with increased thickness, concurrently restricts light transport and collection.

To overcome this hurdle, we have been developing strategies to enhance composition transparency by mitigating porosity, a significant contributor to light scattering. This is achieved by consolidating powders at elevated temperatures, capitalizing on the disparate melting points of the two component materials. Examples of two materials of interest include CsI(Tl)/LiF and ZnS(Ag)/LiF.

In this presentation, we will delve into our ongoing efforts in the development, optimization, characterization, and application of these innovative, cost-effective composite scintillators tailored for neutron imaging. Our work aims to contribute to the advancement of neutron imaging technology, offering solutions that transcend the limitations of conventional scintillator materials and open new frontiers in scientific and industrial applications.

Photograph of a 3 mm cold pressed CsI-LiF composite on a backlit (high porosity)

Comparison of 1mm hot pressed CaF_2(Eu)-LiF composite (left, low porosity) and ZnS/LiF cold pressed phosphor on a backlit (right, high porosity)



Example of excellent pulse shape discrimination (PSD) of CsI-LiF composite crystal

Orientation-Dependent Grain Level 3D Strain Evolution in Oligocrystalline Coniga

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Understanding the microstructure of polycrystalline and oligocrystalline materials, in terms of the size, position, and orientation of their individual grains, is integral for enhancing our understanding and potential improvement of their mechanical and functional properties. Three-dimensional neutron and X-ray diffraction tomography methods have both proven efficient at providing grain-scale morphology reconstructions of polycrystalline samples [1-5]. In addition, monochromatic X-ray tomographies have been applied for in-situ strain mapping by tracking how the diffraction spots in a tomography move as stress is applied [6], thereby providing important information on the deformation-behavior of the system.

Here, we present results on grain-resolved strain mapping performed based on Laue three-dimensional neutron diffraction tomography (Laue 3DNDT). Neutrons are more efficient at penetrating bulky samples made up of the elements typically seen in functional alloys, and the use of the white beam both increases the overall experimental efficiency and makes it possible to detect phase transitions and grain re-orientations within a single projection in the tomography. The underlying analysis is based on our novel Laue 3DNDT approach [7-8], in which the initial indexing of the undeformed state is performed using a forward-modelling approach. Subsequent stress states, obtained via in-situ loading of the sample, are then analyzed by fitting grain-resolved strain tensors congruent with the observed diffraction spot movements. We will also discuss the challenges in the analysis related to the utilization of a white beam.

Experimental data using this novel strain mapping method will be presented featuring a CoNiGa sample, which has been prepared using hot-extrusion to promote grain growth and a homogenous oligocrystalline microstructure [9]. The CoNiGa sample has been chosen both for its scientific relevance, being a ferromagnetic shape-memory alloy exhibiting strong anisotropic effects, as well as for its suitability to demonstrate the potential of our method, given the size of the sample and the large grains in the mm-range. We will present the evolution of the strain tensor elements per grain as a function of applied compressive stress and compare them to single-crystal expectations.

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Shape and Size Distribution of the Magnetic Domain Structure in Electrical Steel Measured with Neutron Grating Interferometry

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Electrical steel sheets are used as the magnetic core of electrical engines. Currently the essential guidance of the magnetic flux inside a magnetic core is achieved by cutouts. However, these cutouts create thin structures, reducing the mechanical strength of the electrical steel sheets. This limits the achievable maximum rotational speed and therefore the energy efficiency of the engine. Hence, it is of great interest to develop magnetic flux barriers that do not compromise the structural integrity of the electrical steel sheets.

Currently, we examine a novel approach to guide the magnetic flux by deliberately introducing residual stress through embossing [1,2,3,4]. Residual stress in the electrical steel sheets reduces the mobility of the magnetic-domain walls due to the magneto-elastic effect, resulting in a reduced response of magnetic domains to external magnetic fields [5], effectively decreasing the local magnetic permeability while maintaining the mechanical strength.

The interaction of the magnetic moment of neutrons with the magnetic-domain structure in ferromagnetic materials causes Ultra-Small-Angle Neutron Scattering (USANS). USANS is mapped by the Dark Field Image (DFI) of a neutron grating interferometer as it probes the real space correlation function of the system at a given correlation length. In an applied magnetic field, a change in magnetic-domain size results in a change of the DFI signal [6]. Hence, neutron grating interferometry (nGI) maps the magnetic-domain distribution of bulk ferromagnetic materials [7]. Due to the single dimensionality of typical nGI systems they are only sensitive to scattering along a single axis i.e., perpendicular to the grating lines. But by scanning the orientation of the sensitivity direction of the nGI and probing the correlation function at different correlation lengths the dominant structure size and orientation of the magnetic domains can be extracted. Here we show the change in the spatial distribution of domain structure size and orientation during magnetization of embossed magnetic flux barriers.

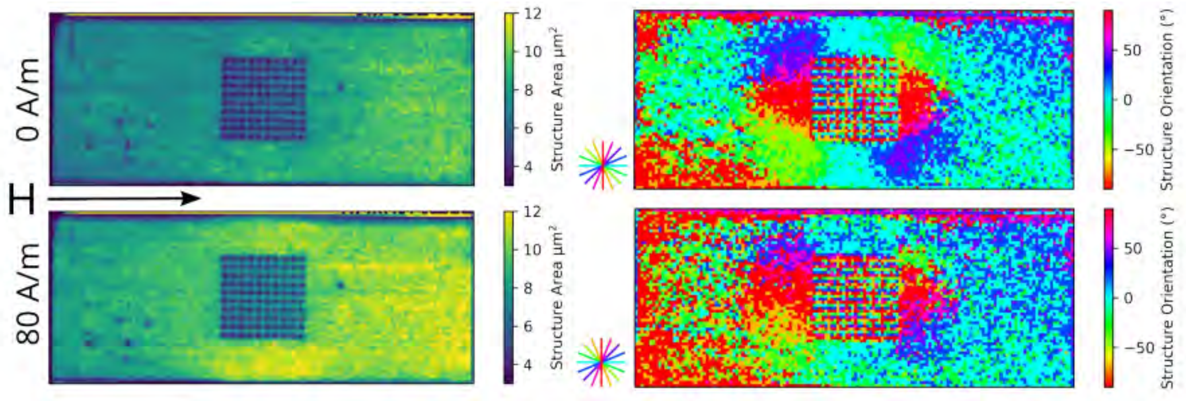

Figure 1: Spatial distribution of magnetic structure area (left) and orientation (right) as calculated from correlation functions probed with nGI for 0 and 80 A/m applied magnetic field parallel to the long edge of the ES.

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Observation of the Macroscopic Magnetic Domains in Silicon Steel During Magnetization with Polarized Neutron Imaging

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In electrical engineering, suitable magnetic cores are often a key requirement for high performance and efficiency. Grain oriented (GO) silicon steels stand out for their use in transformers, since their strongly textured crystal structure results in uniaxial magnetic properties matching the application. A challenge in studying the magnetic behaviour is that most techniques are either insensitive to local variation, since they integrate over large sample volumes (magnetization & magnetic susceptibility) or are restricted to the sample surface (Kerr-effect microscopy [1]).

In contrast, polarized neutron imaging (PNI) [2] provides spatially resolved measurements of local bulk magnetic properties within the sample. In recent years, applications and variants of the technique have been developed to enable the visualization of large magnetic domains [3] or magnetic vector-fields [4].

One such technique uses neutron spin-rotation and produces images that capture the changes of neutron beam's spin-polarization induced by the sample's magnetism. Bulk magnetic order (domains) and magnetic interfaces (domain walls) can be clearly distinguished and quantitative characterizations of the domains can be obtained from further analysis.

Here, we present a PNI study of the magnetic domain structure in a GO silicon steel sheet at various magnetization states. The foundation of this study is the development of a suitable magnetic sample environment. The strong magnetic response of silicon steels and the necessity to apply a suitable field for magnetization both interfere with the highly sensitive magnetic setup of a polarized neutron instrument. Aided by finite element and ray tracing simulations we have developed a setup that enables such spin-rotation PNI experiments.

Using our magnetic setup at the BOA instrument (SINQ, PSI), we observed the changing domain structure of the sample during initial magnetization and magnetization reversal. We could track the growth and decline of individual domains up to the merging of domains when approaching magnetic saturation. On a larger scale, regions in different states of magnetic order and disorder could be distinguished, as well as the impact of grain boundaries. These regions have also visibly affected the macroscopic flux distribution in the sample. In addition, the measurements allowed us to determine the local internal field in the domains, which has virtually the same value of 1.71T across the sample and is identical at different magnetization states. The value is in good agreement with published magnetization measurements [5]

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Neutron Diffusive Dark-Field Imaging Using a Structured Mask

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This study explores extraction of position-dependent diffusive dark-field signals using the speckle-tracking method, which is widely utilised in X-ray imaging. Such dark-field signals provide information regarding spatially-random unresolved micro-structures within a sample. We have implemented a neutron speckle tracking technique to extract these signals, demonstrating promising efficiency compared to existing multi-grating methods. Structured masks were designed and fabricated for this purpose. Subsequently, we imaged a diverse range of potential dark-field samples (over ten in total), using the Dingo neutron beamline at the Australian Nuclear Science and Technology Organisation (ANSTO).

Four random and fractal masks with 10 µm resolution were fabricated on a 30 mm × 30 mm glass substrate. One of the masks were a random binary mask, while the other three masks were various types of random fractal. These binary masks consist of opaque and transparent sections, where the opaque regions, made of Gadolinium, are neutron absorbent. The experimental setup was as follows. First, the mask was placed in the neutron beam. Then a range of samples, mounted onto an aluminium plate, were located between the mask and the detector and as close as mechanically possible to the mask, to prevent phase effects from the mask to the sample plane. The samples ranged from Graphite powder and Diamond powder to a feather, human hair, Polymorph thermal pellets, block copolymer, and Hyderabad Steel. All samples were imaged with the two large fractal masks along with a 10 mm in-pile collimator. The experiment was also repeated with a 2 mm Cd pinhole at the slits before the He flight tube approximately 5 m upstream from the sample.

Data for each experiment were gathered in a two-step process. The first step involved collecting images of the mask and the sample at a single transverse position. The second step focused on collecting mask-only images. To enhance precision, five images were collected for each scenario, and subsequently averaged to mitigate the influence of gamma rays. Upcoming data analysis will leverage mathematical models and software developed by our research group [1,2]. Anticipated outcomes include extraction of diverse position-dependent diffusive dark-field images from various samples and understanding how quantitative information regarding sample micro-structures may thereby be obtained.

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Development of an Achromatic Neutron Lens

Manoraj Dhanalakshmi Veeraraj[1], Di Qu[1], Peng Qi[1], Matteo Busi[2], Joan Vila Comamala[1], Markus Strobl[2], Christian David[1]
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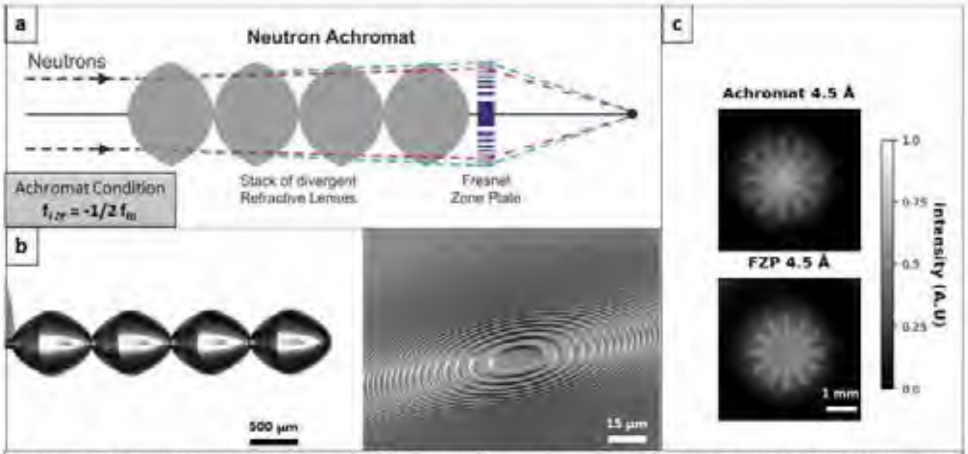
mano.dhanalakshmi-veeraraj@psi.ch

Focusing chargeless and weakly interacting neutrons poses a severe challenge for realizing a high-resolution full-field neutron microscope. The performance of such a setup critically relies on the neutron optics to obtain a magnified image of the sample on the detector. Thus, for a given beamline hutch length, a neutron lens providing sufficient magnification is required. While diffractive and refractive lenses for cold neutrons have been previously demonstrated [1,2], their full potential has been constrained by strong chromatic aberration. Minimizing chromatic blurring using monochromators at the cost of reduced flux results in impractical long exposure times. A neutron achromat, comprising both refractive and diffractive lenses, has been theoretically proposed [3] as an optimal objective for a neutron microscope. This contribution reports on the first experimental steps towards the development of such a neutron achromat.



a) Schematic of achromatic focusing using a combination of a divergent refractive lens (RL) and a focusing Fresnel zone plate (FZP) **b)** SEM images of a 1.2 mm Diameter Nickel FZP **c)** 6x magnified Neutron microscope images of a 3 mm Diameter Gd Siemens star formed by Neutron achromat designed for 4.5 Å (top) and an equivalent FZP of similar focal length and diameter (bottom) both resolving structures upto 140 µm on the object.

Following the first experimental demonstration of an achromat for X-rays[4], a neutron achromat can be constructed by combining a focusing Fresnel zone plate (FZP) and a defocusing parabolic refractive lens (RL) having a focal length fulfilling the condition of $f_{FZP} = -1/2\ f_{RL}$ as illustrated in Figure a). Upon careful survey of neutron optical constants, the first neutron achromat was implemented using a Ni FZP and a Diamond RL designed for a neutron wavelength of 4.5 Å with a focal length of 1 meter. Figure b) shows the FZP fabricated using state-of-the-art electron-beam lithography and electroplating techniques. The parabolic diamond RL was machined using a water jet-guided laser turning technique. A successful proof-of-concept demonstration of a neutron microscope implemented with a neutron achromat as an objective lens was recently conducted at the BOA Beamline at the SINQ, Switzerland. This beamtime was aimed to establish a comparison of the broadband imaging performance of the achromat and an equivalent FZP with 6x magnification as shown in Figure c). Initial observations suggest that the FZP has a higher signal-to-noise ratio (SNR), but its resolution is ultimately constrained by chromatic aberration. Although the achromat was anticipated to exhibit reduced chromatic blurring in the image, the lower SNR due to absorption in CRL complicates a definitive assessment. Nevertheless, this demonstration holds significant promise, encouraging further advancements in e-beam lithography that could enhance the performance of the achromat ultimately aiming at micron-scale resolution by achieving large magnifications.

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[4] Kubec, A. *et al.* An achromatic X-ray lens. *Nat. Commun.* **13**, 2–8 (2022).

Enhancement of Spatial Resolution in High-Speed Neutron Imaging Using a Multi-Slit Collimator

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Naoya ODAIRA[1], Keisuke KURITA[2]

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[2] *Japan Atomic Energy Agency*

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In the field of neutron imaging, the challenge of simultaneously achieving high spatial and temporal resolution is significant, particularly for dynamic imaging applications. Traditional approaches, such as multi/single-pinhole collimation, often face limitations in neutron flux, affecting the imaging speed. This study introduces a groundbreaking method employing multi-slit collimation to overcome these challenges, offering a novel pathway to high resolution neutron imaging without compromising on temporal capabilities. Our approach leverages the unique advantages of multi-slit collimation, wherein multiple narrow slits allow for a greater neutron flux compared to pinhole systems, thereby enhancing imaging speed while maintaining spatial resolution. This design significantly improves the neutron economy, enabling faster image acquisition times and facilitating the observation of transient phenomena with exceptional detail. The research was conducted using a specialized multi-slit collimator integrated into a high-flux neutron imaging facility at the JRR-3. This setup allowed for the precise control of slit dimensions and configurations, optimizing the balance between spatial resolution and imaging speed. Advanced image reconstruction algorithms were developed to process the data captured through this collimation system, effectively reducing noise and improving image quality. Experimental results demonstrate the efficacy of the multi-slit approach in capturing high-resolution images of dynamic processes, such as fluid flow in porous media and phase transitions in materials, with unprecedented temporal resolution. The technique showcases significant improvements over existing methods, opening new avenues for applications in materials science, engineering, and beyond.

Development Plans for the NIST Cold Neutron Imaging Instrument

Daniel S. Hussey[1], **Youngju Kim**[1,2], **M. Cyrus Daugherty**[1], **Jacob M. LaManna**[1], **David L. Jacobson**[1], **Chet O. Speegle**[3], **Nicholas E. Thomas**[3]

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Figure 1 First mirror of the objective for the Wolter optics microscope.

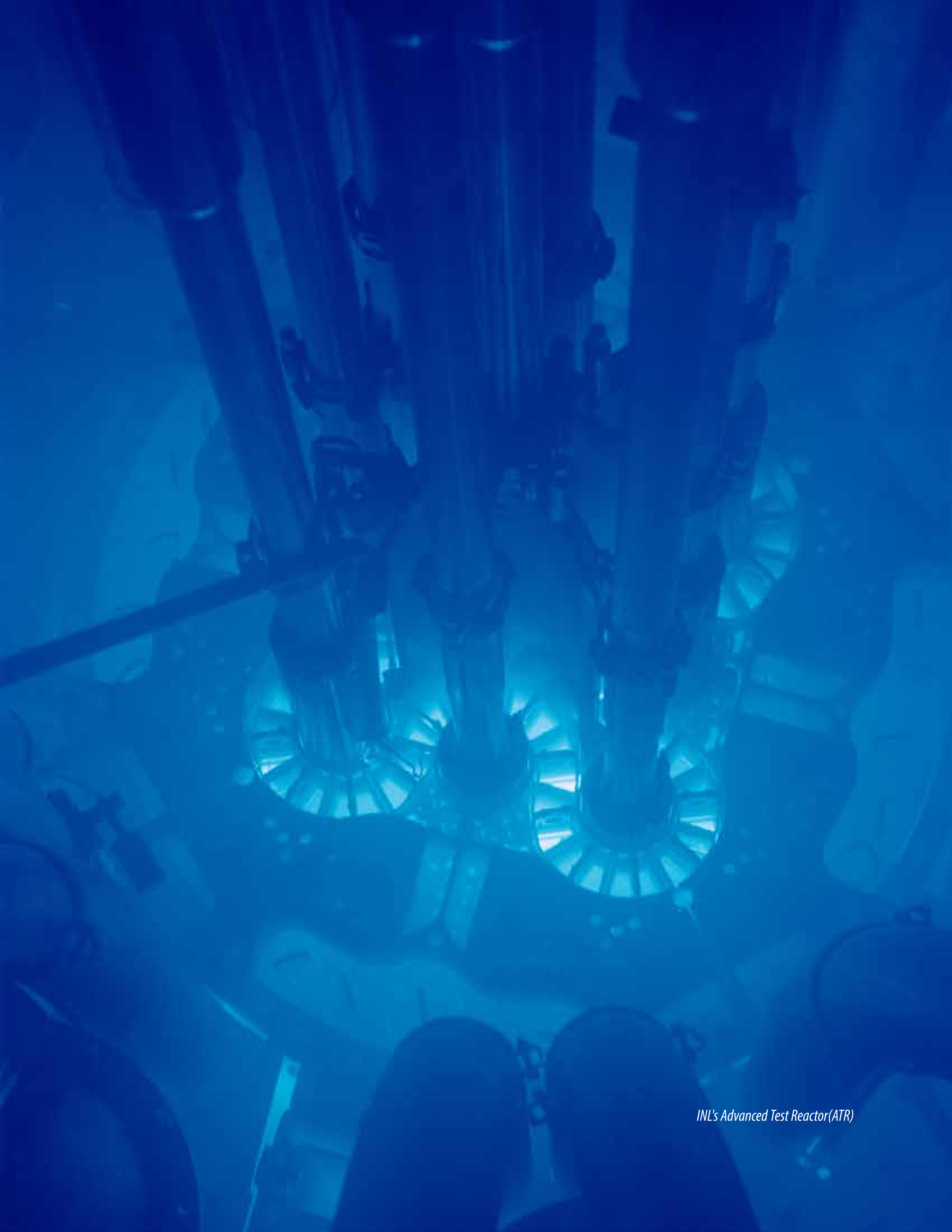
The cold neutron imaging instrument (CNII) began operating in August 2016 at the end position of the NIST Center for Neutron Research neutron guide 6 (NG6e). The impetus for the CNII was to house a neutron microscope based on Wolter optics. The development and fabrication of the Wolter optics has experienced multiple (mostly non-technical) delays, and the first mirrors that comprise one shell of the condenser and one shell of the objective have been fabricated and characterized. We will discuss the potential impact of these mirrors and the remaining challenges to completing the design proposed in [1].

With a cold neutron spectrum (peak of the distribution about 0.45 nm), the beamline enables the development of other wavelength selective methods. Most such applications have relied on a double crystal monochromator composed of highly oriented pyrolytic graphite crystals. Bragg edge imaging was used for strain measurements as well as crystal phase volume fraction determination. A recent focus of the instrument development has been on dark field tomography. The project was dubbed “INFER” as it relies on grating interferometers and relies heavily on compressed sensing and machine learning for segmentations to facilitate inferring meaning from the measurements. The chosen interferometer configuration is a two grating far field interferometer and, despite lack of access to neutrons at NIST due to the ongoing recovery from the incident on 03 FEB 2021, significant progress has been made on grating fabrication and instrumental developments. The status of the project will be reviewed, and results obtained from upcoming visits to other facilities will be presented.

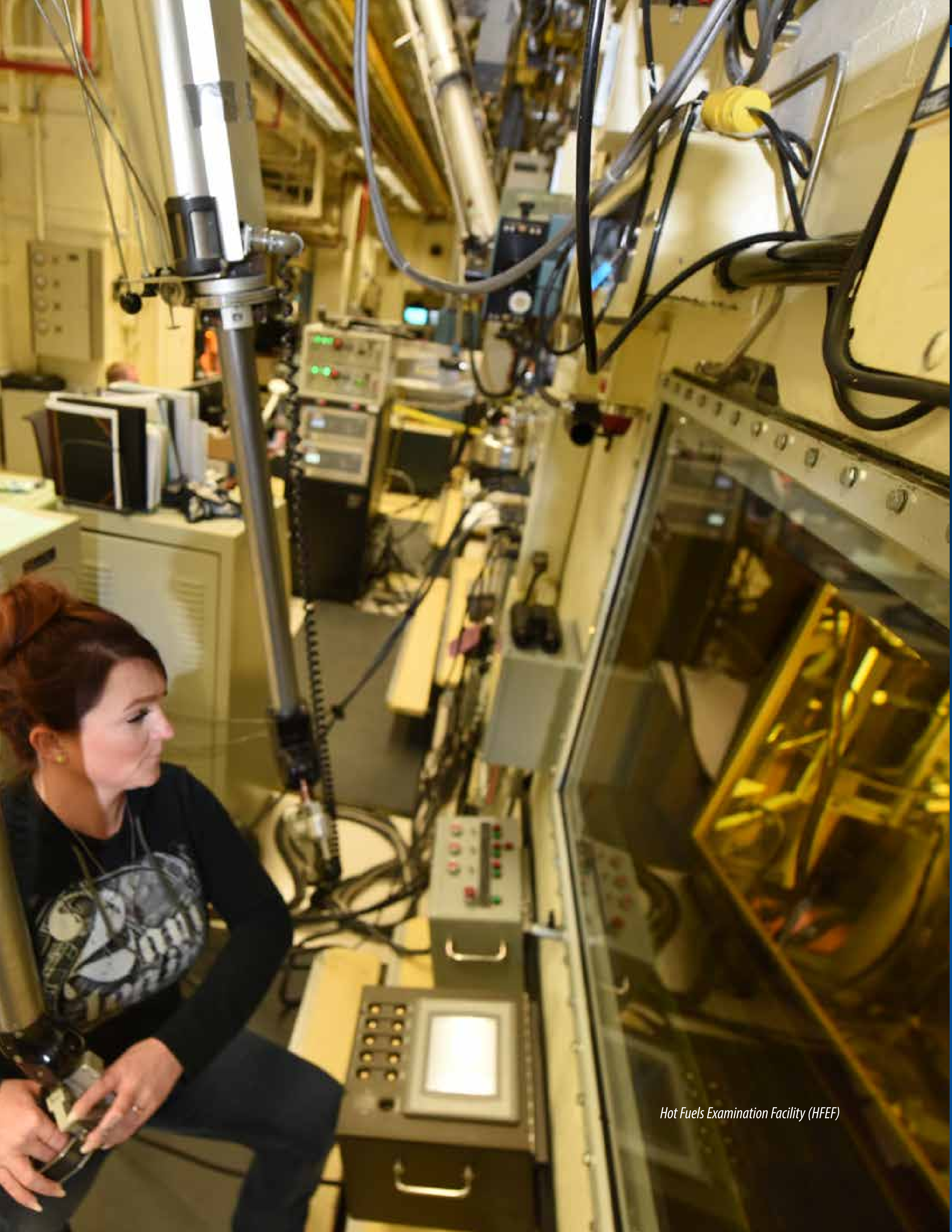
The NCNR expects to upgrade the cold source to increase cold neutron production for wavelengths greater than 0.5 nm. During this effort, we will replace the original mirrors of NG6 with m=2 supermirrors that will also eliminate the background from the direct view of the reactor core. The upgraded instrument area and schedule for this work will be discussed.

[1] D.S. Hussey et al, NIM A 987 (2021) 164813
[2] D.A. Pushin et al, PRA 95 (2017) 043637.

Acknowledgments: The authors are grateful for beamline assistance at **MARS** (Y. Zhang, J. orres, and E. Stringfellow), **ASTERIX** (A. Long and S. Vogel), **ENRF** (T.J. Kim, J. Kim**), NeXT-Grenoble** (A. Tengattini, A. Fedrigo, L. Helfen), and the INFER collaboration: K. Weigandt, P. Bajcsy, M. Huber, P. Kienzle, C. Wolf, S. Robinson, N. Klimov, P. Sathe, R. Murphy.



INL's Advanced Test Reactor(ATR)



Hot Fuels Examination Facility (HFEF)

WCNR 12

EXHIBITORS

Event-Mode Neutron Imaging Detector

Losko et al., Scientific Reports 11 #21360 (2021)

Scintillator-based neutron imaging: Low resolution, high background, mainly qualitative information

Event-mode imaging: High resolution, no gamma background, image contrast can be used for quantitative image analysis

Amsterdam Scientific Instruments

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ASI designs and manufactures advanced detection systems based on **CERN Timepix-3 technology.** For neutron scientists ASI produces Chronos Telesto with 256 x 256 pixels and 512 x512 pixels
Chronos detectors are sensitive down to single photons and operate in data-driven or frame-based mode with a time resolution of 1.56 nanoseconds per photon.

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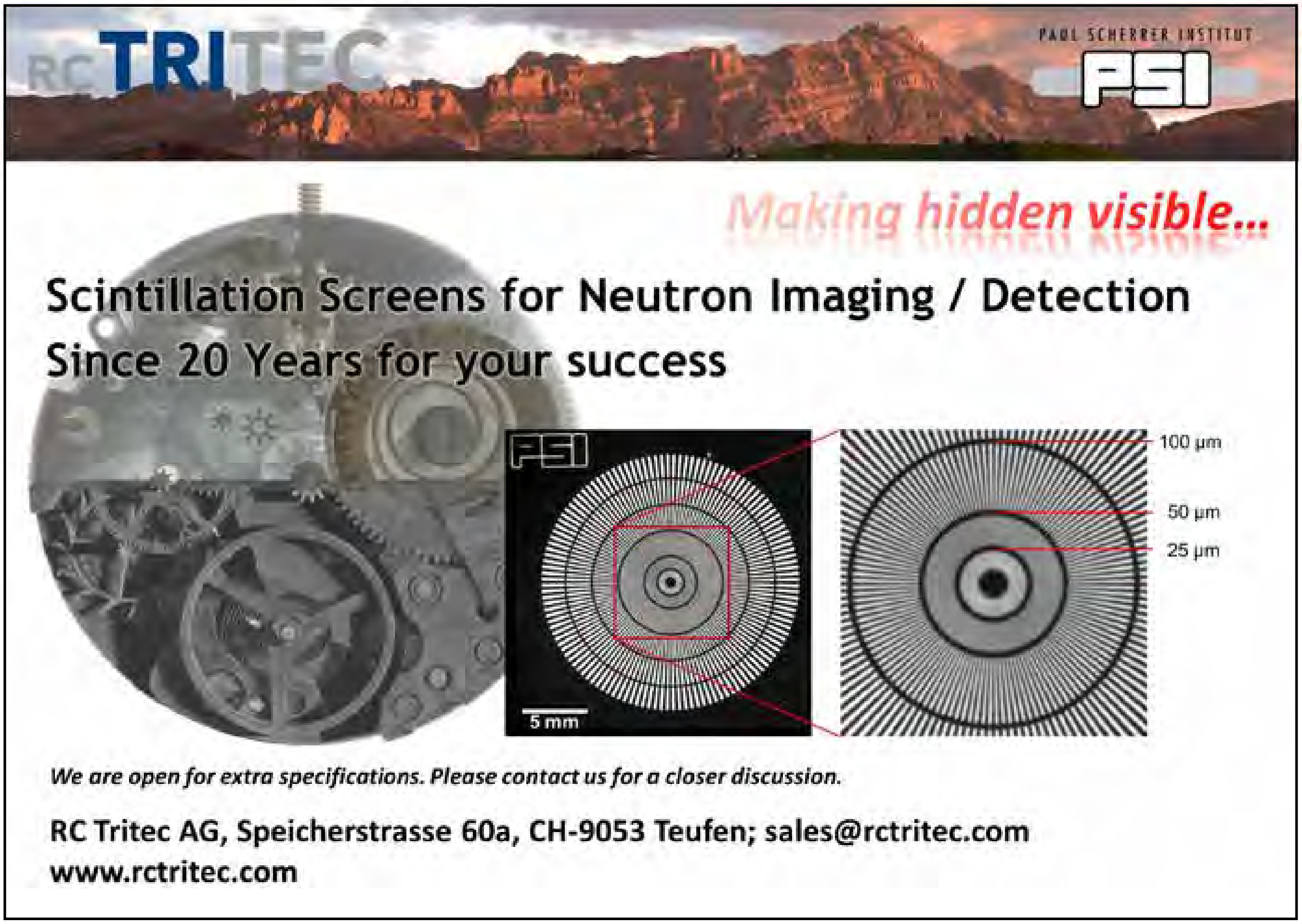

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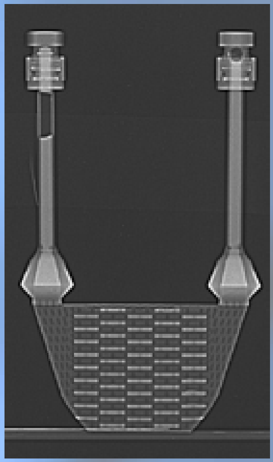
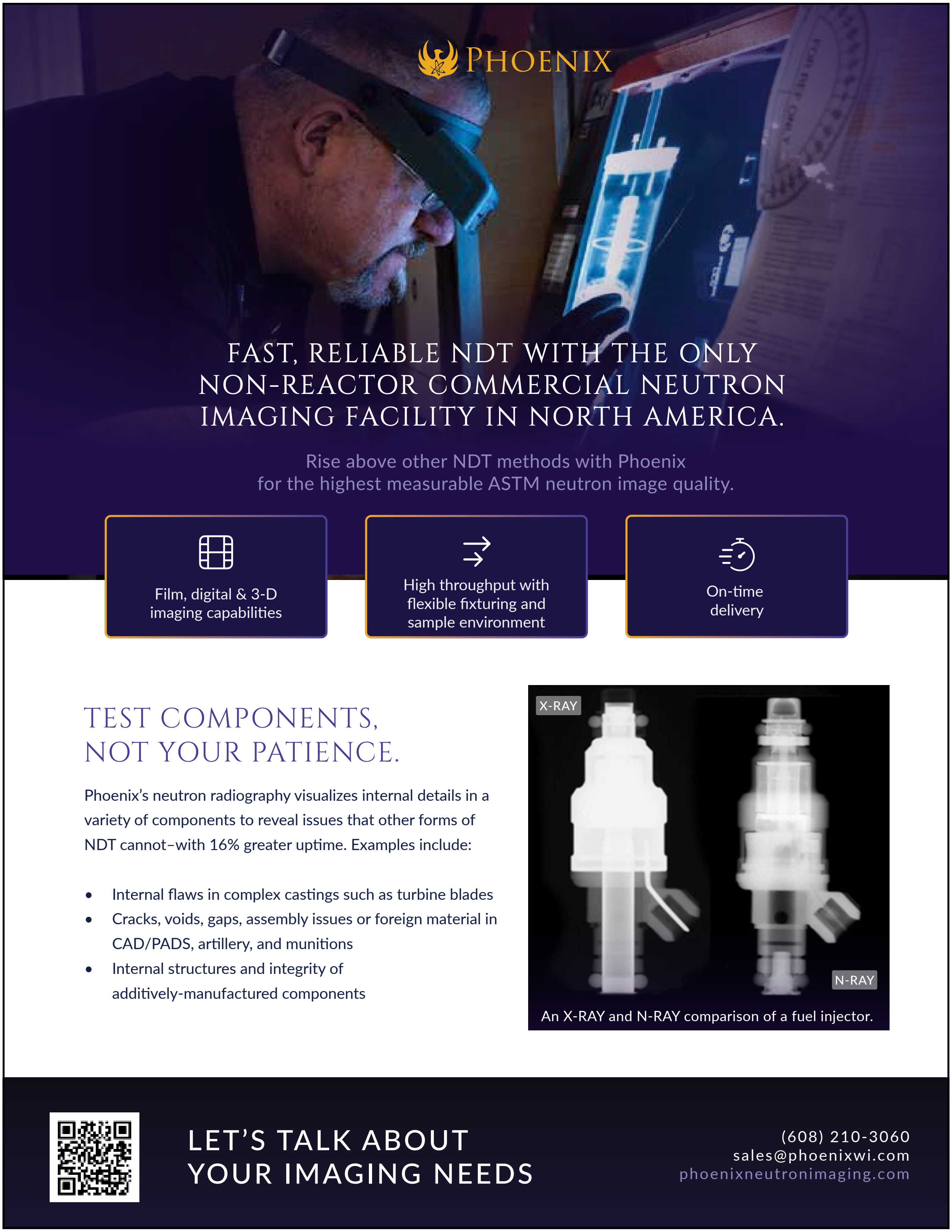


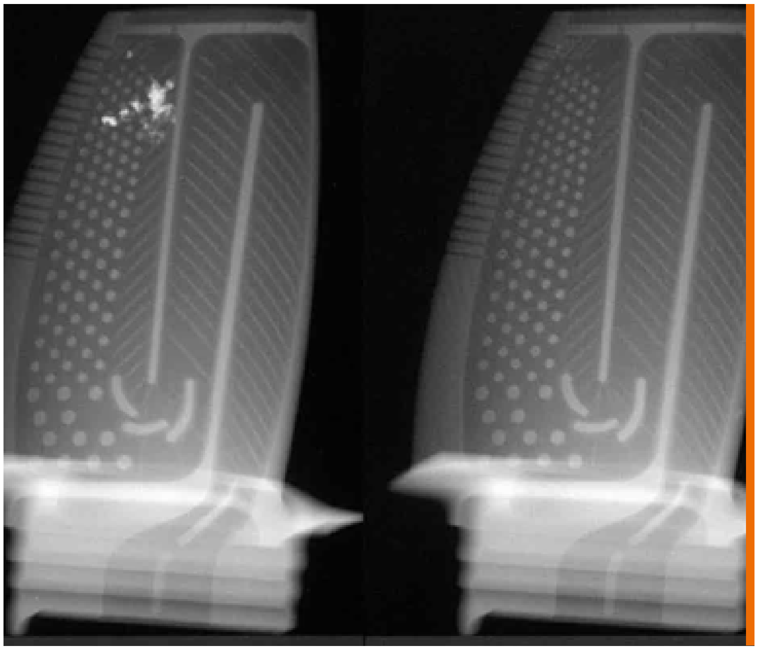


NRAY SERVICES

Applus+ NRAY is a leading provider of neutron radiography services

Applus+ NRAY performs routine inspections on turbine blades and vane segments, using neutron imaging to detect residual cores during the manufacturing process. Additionally, it examines aircraft fuel nozzles to identify carbon build-up accumulated during use and assesses composite fan blades for manufacturing defects, offering an alternative to X-ray CT.

Applus+ NRAY is a leading provider of neutron radiography services. Its non-destructive testing examinations are fit to meet the challenging demands of a wide range of international and global clients from aerospace, defence, space, manufacturing, and research & development. The company was founded in 1994 in Dundas (Ontario, Canada) and a second facility was established in Raleigh (North Carolina, USA) in 2008. In 2014, it joined the Applus+ group. NRAY is a division of the Applus+ Laboratories group.



Example image of aircraft turbine blades imaged using Neutron Radiography. Rejectable part (left) containing unwanted residual core material (bright white) left over from the casting process and an acceptable part (right).

Neutron imaging supplies

Applus+ NRAY manufactures, distributes, and re-sells neutron radiography and imagining supplies, equipment and materials. These neutron imaging supplies include image quality indicators built to ASTM standards, conversion screens, and vacuum cassettes which are used by neutron radiography facilities around the globe.

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Neutrons for New Discoveries and Solutions

Breakthroughs in medicine, energy, technology, and industry follow advances in the understanding of materials. Oak Ridge National Laboratory (ORNL) is the US epicenter of one of the most powerful techniques for exploring the nature of materials — neutron scattering.

ORNL hosts two of the world's most powerful sources of neutrons for research: the Spallation Neutron Source (SNS) and the High Flux Isotope Reactor (HFIR), which each produce different, but highly useful and complementary types of neutron beams. Because neutrons have no electrical charge, they can easily pass through materials — even dense metals — without altering them, revealing information about their atomic structure and other properties.

Neutron scattering is used by scientists and many industries — such as automotive, aerospace, steel, defense, energy production and storage, data storage, and biomedicine — to address many of the major scientific and societal challenges of the 21st century.

Ensuring US Leadership

The Proton Power Upgrade (PPU), planned for completion in 2025, will increase the SNS beam power and significantly enhance its capability to support the US research community. The PPU is necessary to support a Second Target Station at the SNS to maintain US competitiveness in materials development as new European and Asian neutron facilities come online.

The Second Target Station (in white in the illustration at left) will complement existing SNS and HFIR capabilities.

597
Scientific publications in FY 2023*

1,177
Unique users in FY 2023

85,442
Hours of beam time in FY 2023

1,677
Total experiments in FY 2023

> "We can work together and really push our understanding of the world."
>
> —Physicist **Bianca Haberl**

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597 total publications including 502 peer-reviewed journal articles

Impacts and Collaborations

- **Fighting COVID:** Neutron studies at SNS and HFIR helped researchers better understand how the SARS-CoV-2 main protease binds amino acids expressed by the virus. This has already helped in developing antiviral molecules and now in discovering new drugs that can remain potent against emerging COVID-19 variants.
- **Safer bridges:** Columbia University researchers used neutrons at SNS to study breaks in suspension bridge cable wires inside the cable and how they affect cable strength and bridge safety. Neutrons enabled nondestructive studies of the wires to help develop more cost-effective cable maintenance methods.
- **Safer, greener appliances:** Scientists at HFIR helped develop an add-on device that eliminates the acidic condensation and greenhouse gases produced by both new and older gas furnaces and other gas appliances.
- **Stronger glass:** Researchers from Corning use neutrons to study how silica behaves as it heats and cools. Better understanding of glass production means more durable glass for mobile devices, windshields, and TV screens.
- **Safer batteries:** Researchers at SNS used neutrons to peer inside a solid-state battery. They found its safer, longer-lasting performance results from a stabilizing layer, across which charged lithium atoms flow quickly.
- **Reliable aircraft:** NASA and Honeywell Aerospace used neutrons at SNS to examine welds used in turbines to facilitate producing more reliable aircraft components.

SNS is an accelerator-based facility that provides the world's most powerful pulsed neutron beams for scientific research and industrial product development. SNS delivers short pulses of protons — 60 times a second — to a target where neutrons are produced by a "spallation" process and sent down beamlines to sophisticated instruments used by researchers.

HFIR uses uranium-235 as the fuel to generate the highest rate of flowing neutrons, or neutron "flux," available for research in the United States.

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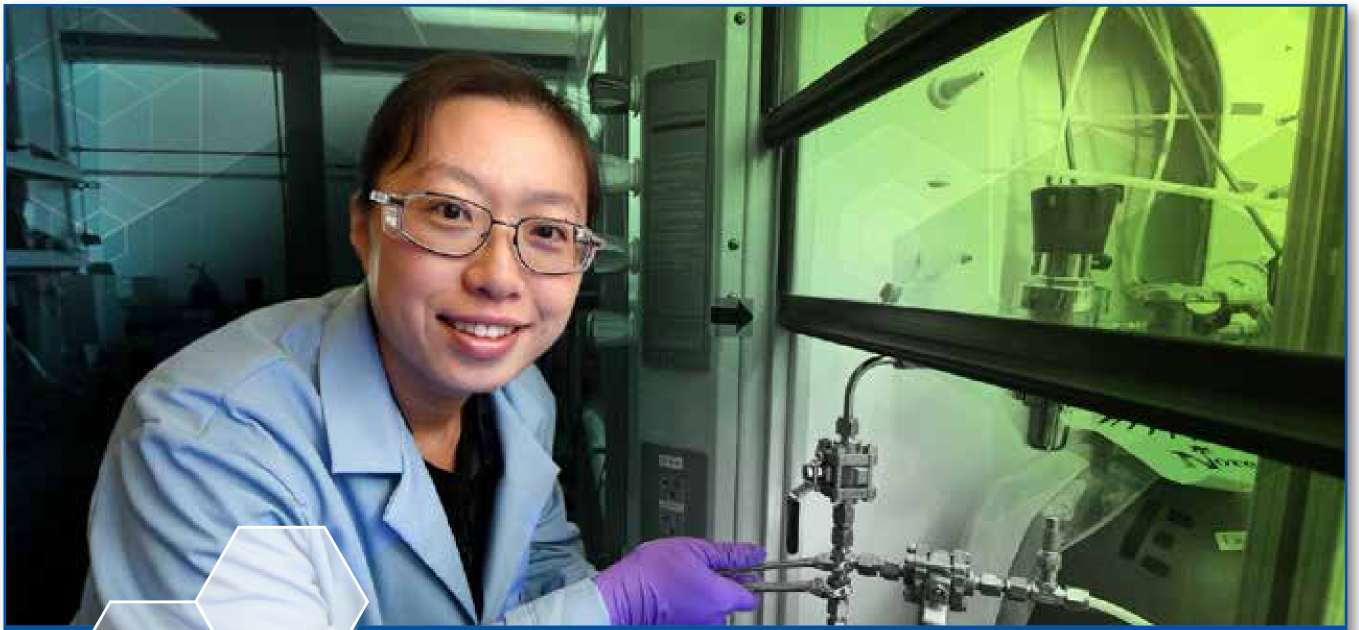

INL Overview

Our innovations help address America's energy, environmental and nuclear challenges through transformative science and technology solutions.

Idaho National Laboratory stands out as a distinctly capable science and technology resource. Notably, the lab serves as the nation's command center for advanced nuclear energy research, development, demonstration and deployment. The lab is home to the unparalleled Advanced Test Reactor and associated assets for post-irradiation examination, fuel fabrication, materials testing and development assets. Leveraging these and numerous other distinguishing features, the lab and its roughly 5,300 scientists, engineers and support staff build on the potential and promise of ideas that can benefit the real world.

A PROUD PAST AND HIGH-PERFORMING PRESENT

INL is one of only 10 multiprogram national laboratories owned by the U.S. Department of Energy. Geographically, INL is the largest lab — the 890-square-mile desert Site also serves as a national environmental research park. INL performs work in support of DOE's mission to ensure America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions.

In the early days, INL was known as the National Reactor Testing Station. Since 1949, the Idaho site has been the location of many pioneering developments in the area of nuclear energy. The world's first usable amount of electricity from nuclear energy was generated in 1951.

Over the years, 52 mostly first-of-their-kind reactors were built at Idaho's national laboratory, creating the largest concentration of reactors in the world. After fulfilling their research missions, most have since been decommissioned.

Although INL today reports up through DOE's Office of Nuclear Energy, the lab conducts a wide range of activities supporting several DOE offices and other federal agencies.

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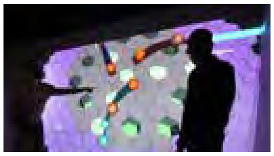

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INL functions as a centralized technology integrator for DOE's Fuel Cycle Research & Development program.

INL has nearly 70 years of experience in nuclear reactor plant design, operations and decommissioning, and nuclear materials processing. The lab's expertise is routinely sought by national and international customers. These standout capabilities are key to supporting DOE's Light Water Reactor Sustainability and Gateway for Accelerated Innovation in Nuclear (GAIN) programs. All INL nuclear operations are based on a long tradition of safe and cost-effective operations.

NATIONAL SECURITY RESEARCH AND TESTING

INL's applied engineering discipline and build-test-build problem-solving approach help the departments of Energy, Defense and Homeland Security as well as industry partners solve significant national security challenges in critical infrastructure protection and nuclear nonproliferation.

The laboratory's signature capabilities, expertise and unique infrastructure assets support efforts to secure industrial control systems from cyber and physical threats, develop advanced nuclear facility safeguards, and design advanced wireless sensors and protocols.

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ENERGY AND ENVIRONMENTAL SUSTAINABILITY

An overarching thrust of INL research is energy security — the nation's greatest challenge for the 21st century. Energy security includes resource security, economic stability and long-term environmental sustainability. Scientists and engineers are exploring solutions to grand challenges in the areas of clean energy development, competing water resource management, and carbon life-cycle options in order to get the right type of energy to the right place at the right time.

INL researchers are configuring and testing hybrid energy systems to increase the range of beneficial energy options, and to demonstrate that renewable, fossil and nuclear energy systems can be successfully and effectively integrated for greater efficiencies. They also validate the efficiency of using clean energy sources to recycle captured carbon dioxide into chemical feedstocks and consumer goods.

Still others in the lab's research community are poised to overcome key barriers facing the U.S. bioenergy industry — by harnessing cellulosic biomass resources and enabling the production of biofuels and other renewable value-added products.

Mainstream research is significantly expanding DOE's ability to evaluate new battery technologies through applied research, development and diagnostics. This work leads to advanced batteries that live longer, are safer and are more cost-effective for electric-drive vehicles.

20-50441_001_R2 (Updated: 2022)

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Outback Steakhouse	970 Lindsay Blvd	208-523-9301	M-Th 1600-2100 F 1600-2200
The Bee's Knees Pub	850 Lindsay Blvd	208-524-1669	Tu-F 1100-2100
Copper Rill Restaurant	415 River Parkway	208-529-5800	M-F 1600- 2030
Snow Eagle Brewing & Grill	455 River Parkway	208-557-0455	M-F 1200-2100
Jakers Bar and Grill	851 Lindsay Blvd	208-524-5420	M-F 1130-2100
Jalisco's Mexican Rest.	325 River Parkway	208-612-0102	M-Th 1100-2200 F 1100-2300
Lucy's Pizzeria	560 West Broadway	208-524-2800	M-Th 1030-2100 F 1030-2200
Smitty's Pancake & Steak House	645 West Broadway	208-523-6450	M-W 0700-1500 Th-F 0700-2100
Smokin' Fins	370 Memorial Dr	208-888-3467	M-Th 1100-2100 F 1100-2200
Olive Garden Italian Restaurant	1305 W Broadway	208-227-0545	M-Th 1100-2200 F 1100-2300
Sandpiper	750 Lindsay Blvd	208-524-3344	M-F 1600-2100
Mahana Fresh	429 S. Utah Ave	208-926-6504	M-Th 1100-2000 F 1100-2100

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Altavita Restaurant	313 Park Ave	208-357-9475	M-F 1130-2000
Carstens' Bakery	243 Cliff St	208-529-3629	M-F 0730-1600
Celt Irish Pub & Grill	398 Broadway	208-881-5128	M-W 1130-2200 Th 1130-2300 F 1130-2400
City Bagels & Bakery	369 Shoup Ave	208-881-5778	M-F 0600-1400
Frosty Gator Pub & Grill	298 D St	208-529-3334	M-TH 1100-2300 F 1100-2300
Great Harvest Bread Co. Café	360 A St	208-522-7444	M-F 0700-1730
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www.museumofidaho.org

Idaho Falls Zoo at Tautphus Park | 2940 Carnival Way | Idaho Falls, ID 83402
208-612-8552 | Daily: 9:30 am – 5 pm
www.Idahofallszoo.org

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Idaho Potato Museum
130 N.W. Main | Blackfoot, ID 83221 | 208-785-2517
Monday – Saturday: 9:30 am – 7 pm | Sunday: 9:30 am – 5 pm
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Yellowstone Bear World
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Daily: 9 am – 6 pm
www.yellowstonebearworld.com
24 miles North of Idaho Falls.

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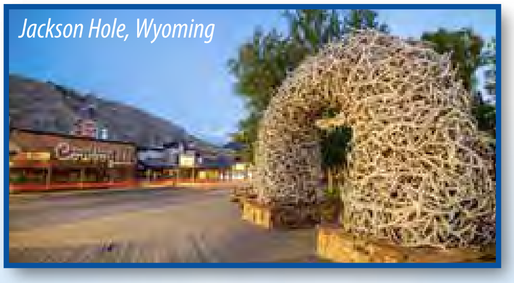
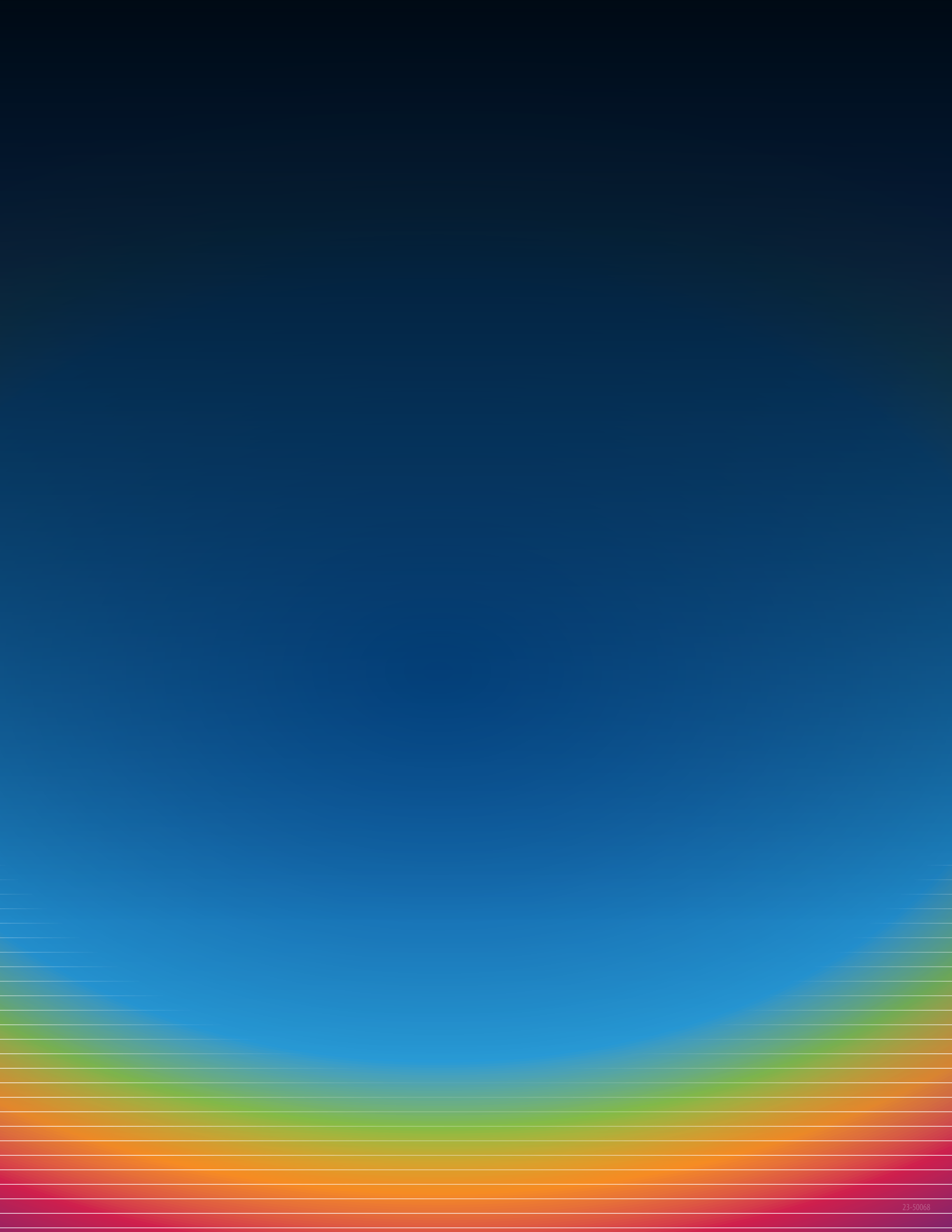

Jackson Hole, Wyoming


Jackson Hole Ski Resort


Old Faithful, Yellowstone National Park



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