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Expertise | Collaboration | Excellence

Overview of Canadian R&D Capabilities to Support Advanced Reactors

Ms. Lori Walters

CNL, Canada

20 March 2024

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INL Idaho National Laboratory
Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

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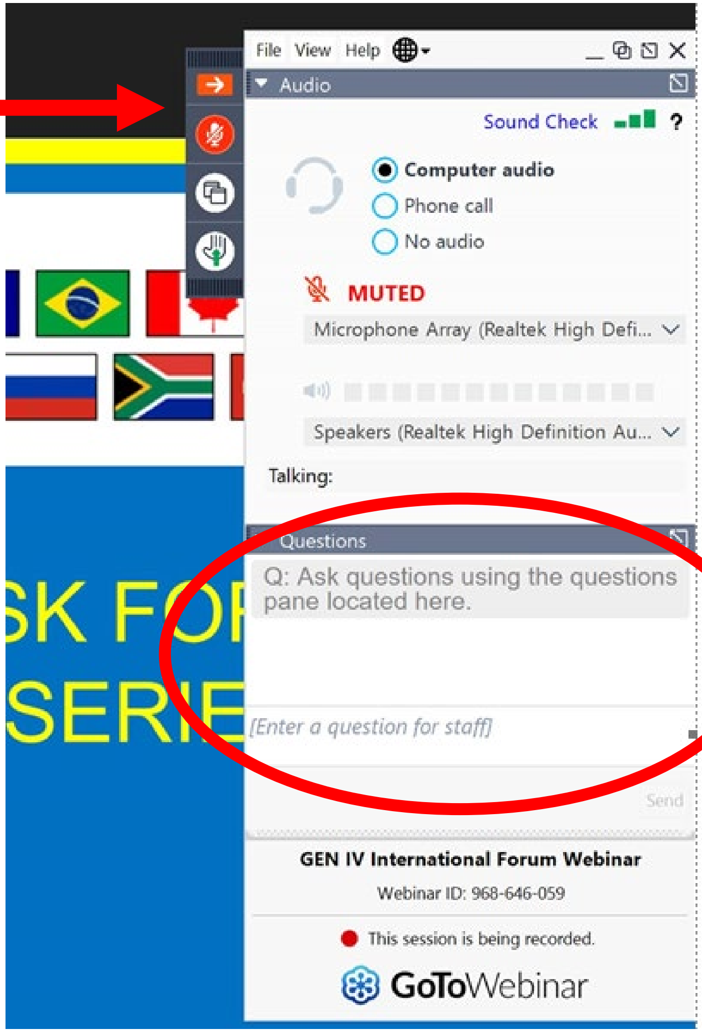

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Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Meet the Presenter

Ms. Lori Walters is currently the Manager of the Advanced Reactor Materials & Chemistry Branch at Canadian Nuclear Laboratories (CNL) where she is responsible for a team of 30 scientists, engineers and technologists who focus on materials and corrosion testing under CANDU and advanced reactor conditions including supercritical water, high temperature gas and molten salt environments.

Lori has been with AECL/CNL since 1995 providing technical and programmatic leadership on both CANDU technologies and GENIV systems.

Lori studied Mechanical Engineering at the University of Manitoba and during her time at CNL has established technical expertise in the areas of irradiation deformation and damage of in-core materials, materials performance, and in-core testing.

Email: lori.walters@cnl.ca

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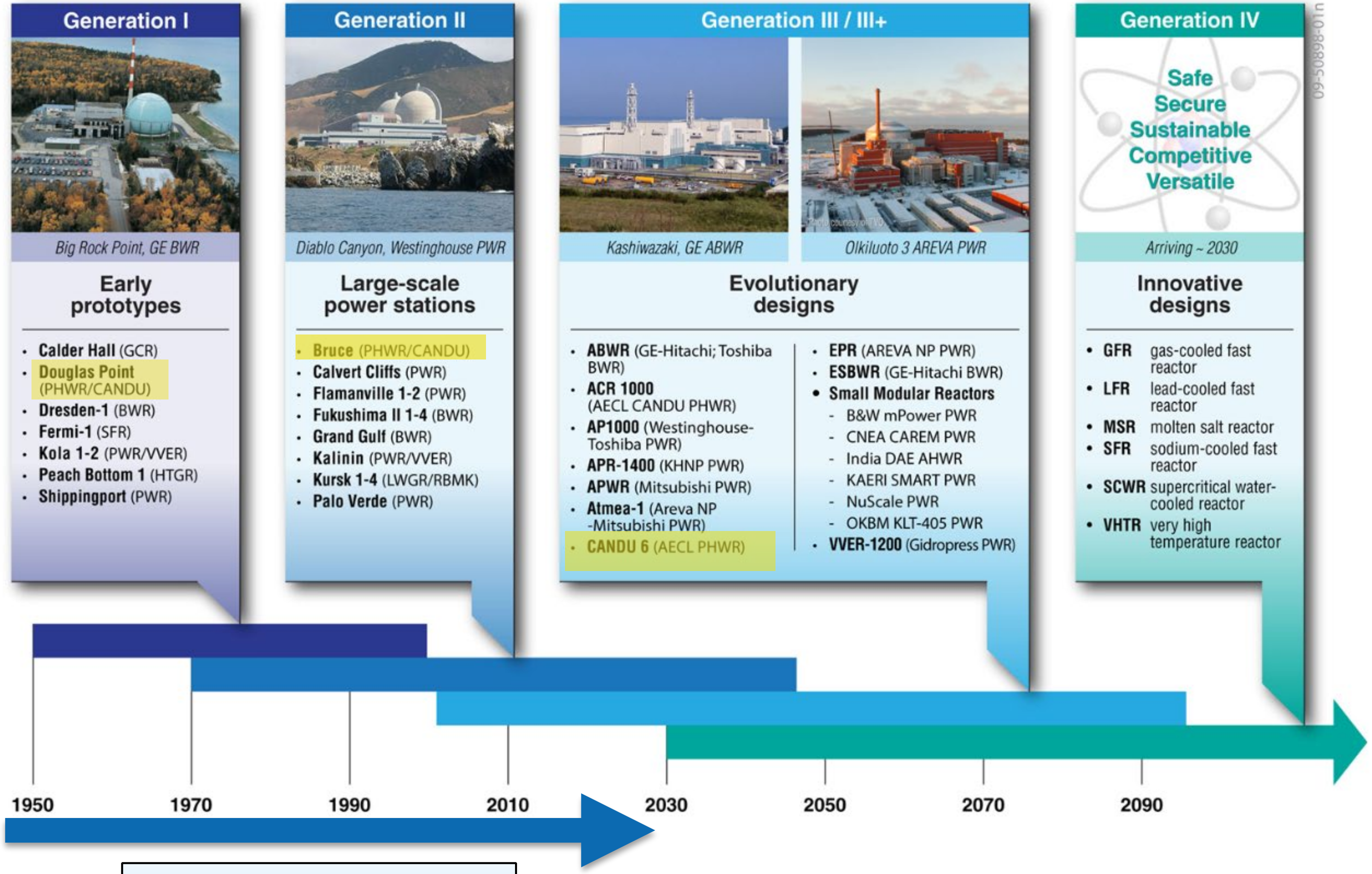
Nuclear in Canada



Early prototypes

- **Calder Hall** (GCR)
- **Douglas Point** (PHWR/CANDU)
- **Dresden-1** (BWR)
- **Fermi-1** (SFR)
- **Kola 1-2** (PWR/VVER)
- **Peach Bottom 1** (HTGR)
- **Shippingport** (PWR)

Large-scale power stations

- **Bruce** (PHWR/CANDU)
- **Calvert Cliffs** (PWR)
- **Flamanville 1-2** (PWR)
- **Fukushima II 1-4** (BWR)
- **Grand Gulf** (BWR)
- **Kalinin** (PWR/VVER)
- **Kursk 1-4** (LWGR/RBMK)
- **Palo Verde** (PWR)

Evolutionary designs

- **ABWR** (GE-Hitachi; Toshiba BWR)
- **ACR 1000** (AECL CANDU PHWR)
- **AP1000** (Westinghouse-Toshiba PWR)
- **APR-1400** (KHNP PWR)
- **APWR** (Mitsubishi PWR)
- **Atmea-1** (Areva NP -Mitsubishi PWR)
- **CANDU 6** (AECL PHWR)
- **EPR** (AREVA NP PWR)
- **ESBWR** (GE-Hitachi BWR)
- **Small Modular Reactors**
  - B&W mPower PWR
  - CNEA CAREM PWR
  - India DAE AHWR
  - KAERI SMART PWR
  - NuScale PWR
  - OKBM KLT-405 PWR
- **VVER-1200** (Gidropress PWR)

Innovative designs

GFR	gas-cooled fast reactor
LFR	lead-cooled fast reactor
MSR	molten salt reactor
SFR	sodium-cooled fast reactor
SCWR	supercritical water-cooled reactor
VHTR	very high temperature reactor

[Summary of GIF organization to develop the next-generation reactors | GIF Portal (jaea.go.jp)](jaea.go.jp)

Canadian Research Reactors

- ZEEP 1945 -1970
- NRX 1947 - 1993
- NRU 1957-2018
- McMaster Nuclear Reactor 1959 – present
- ZED-2 1960 - present
- WR-1 1965 -1985
- Slowpoke 1970 - present

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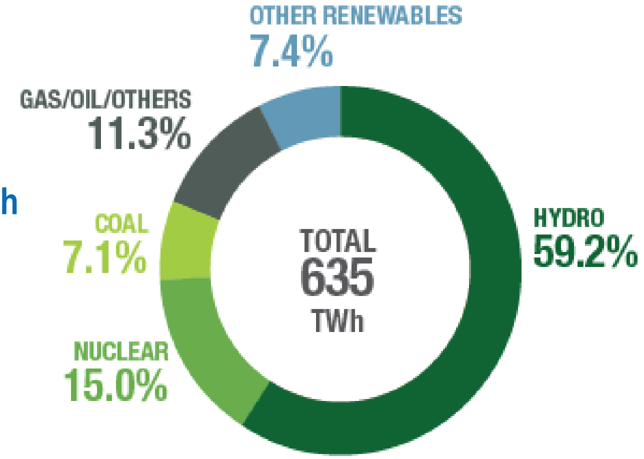
Net-Zero Challenge in Canada

Goal: net-zero emissions by 2050, with a net-zero electricity grid by 2035

- **About 75% of Canada's energy still comes from fossil fuels**, multitude of low-carbon power sources required to serve Canadian residential, commercial, transportation and industrial sectors
- Canadian grid is already fairly "green", but **large-scale electrification essential** to achieve net-zero by 2050
- **Transportation decarbonisation**: likely battery electric for light-duty vehicles, but hydrogen fuel cells are a good fit for large vehicles and/or high duty cycle applications, synthetic and clean fuels
- **Industrial decarbonisation:** renewables such as solar and wind, do not produce industrial heat, only electricity. Canada needs energy solutions not just electricity, heat demand in the winter is 2-3 times that of electricity in northern Canada.
- **No single technology can achieve our goals**. Nuclear energy is part of solution for achieving these objectives. Success will require an "all options" approach, necessitating the use of hybrid and integrated energy system.

CANADIAN ELECTRICITY GENERATION, BY SOURCE, 2019 – 635 TWh



Data from NRCan Energy Fact Book 2021-2022

Potential Markets in Canada

Transmission infrastructure illustration – Tetra Energy

Grid Power

- Canada's electricity total 635 TWh in 2019, held steady
- Forecasted demand as high as 2-3 times demand by 2050

Illustration of industry - https://afry.com/

Industrial Processes

- Oil sands
- Mining
- Hydrogen production

Canadian remote communities - NRCan

Remote Communities

- 81% primarily diesel energy supply
- 92% of communities below $10MW_e$

Three Streams of SMR Development in Canada

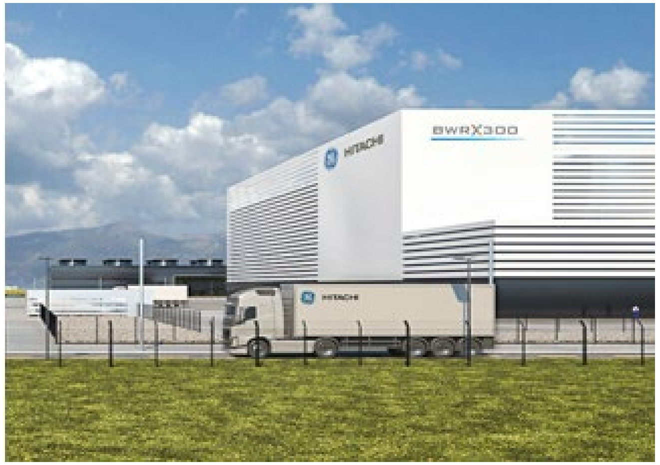


Illustration of GE Hitachi BWRX-300 - https://bindustry.eu/

Gen-III Grid-Scale

- BWRX 300 for Ontario Power Generation and SaskPower deployment

Illustration of Moltex SSR-W – moltexenergy.com

Gen-IV reactors

- ARC-100 partnering with New Brunswick Power
- Moltex SSR-W partnering with New Brunswick Power
- X-Energy and OPG have a framework agreement
- StarCore Nuclear and Terrestrial Energy IMSR applied to CNL demonstration

Illustration of Westinghouse eVinci – brucepower.com

Micro-Reactors

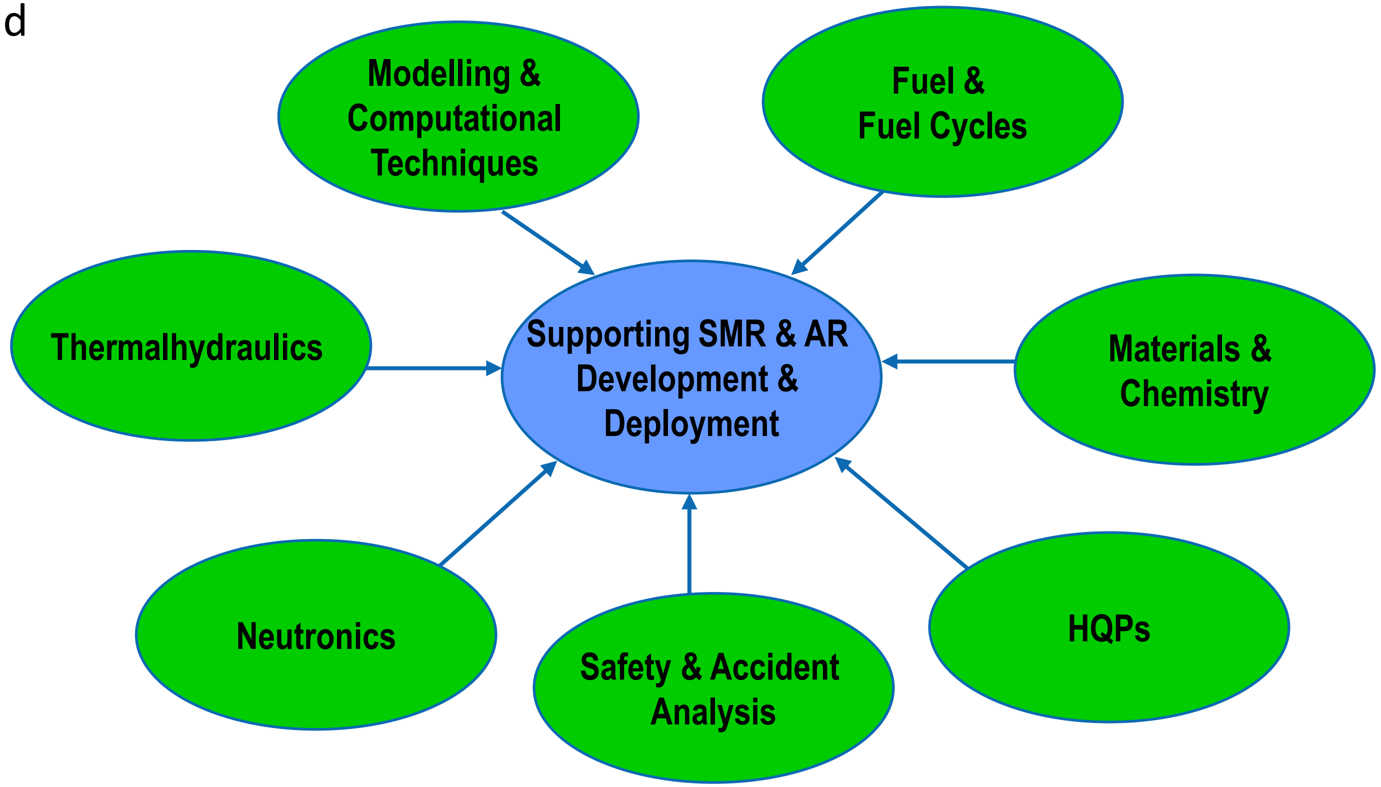
- USNC GFP MMR® applied to CNL demonstration
- USNC GFP MOU with McMaster to study deployment of MMR
- Westinghouse eVinci™ MOUs with Bruce Power and Saskatchewan Research Council

Canadian Capabilities to Support SMRs & Advanced Reactors

Presentation Overview

1. Key facilities/capabilities at Canadian labs and universities

2. Application of R&D capabilities for SMR and advanced reactor systems:
   - Advanced Water-Cooled Reactors
   - Molten Salt Reactors
   - High-Temperature Gas-Cooled Reactors
   - Sodium Fast Reactors
   - Microreactors


Supporting SMR & AR Development & Deployment

Modelling & Computational Techniques

Fuel & Fuel Cycles

Thermalhydraulics

Materials & Chemistry

Neutronics

Safety & Accident Analysis

HQPs

How Canada is Enabling SMRs & Advanced Reactors

Federal Government

- **SMR Action Plan** in 2020 November as a follow-up to the 2018 **SMR Roadmap**
- Canadian Nuclear Safety Commission (CNSC) pre-licensing vendor design review of 12 SMRs
- Funds available to support nuclear sector via Canada Infrastructure Bank, Strategic Innovation Fund, Electricity Predevelopment Program and Future Electricity Fund

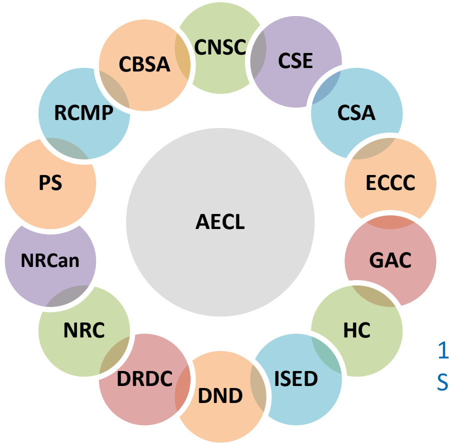
Provincial

- **Feasibility Report** 2021
- Summarizes business case for SMR implementation in each of the provinces Ontario, New Brunswick and Saskatchewan
- **Strategic Plan** 2022
- Ontario, Saskatchewan, New Brunswick, Alberta
- Identified five priority areas for SMR development and deployment: Technology readiness, Regulatory framework, Economics and financing, Nuclear waste management, Indigenous and public engagement

SMR ACTION PLAN: Federal Government, Provinces and Territories, Indigenous, Municipalities, Power Utilities, Civil Society and Education Academia and Research, Industry Associations, Heavy Industry, Supply/Value Chain, SMR vendors

https://smractionplan.ca/

How Canada is Enabling SMRs & Advanced Reactors



14 Federal Family Stakeholders

Canada

AECL Federal Nuclear Science & Technology Work Plan

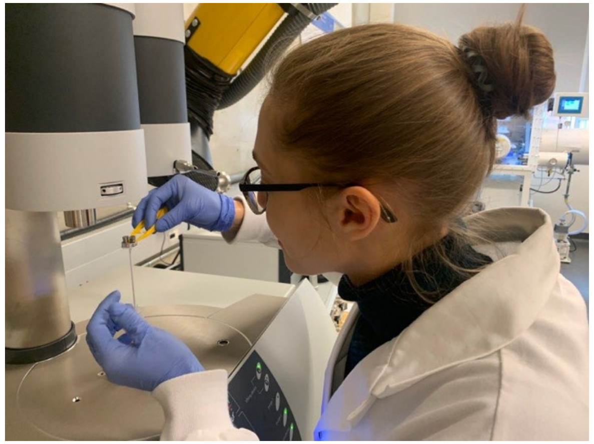
- Helps build a framework for SMR development & deployment in Canada
- Severe accidents, waste, thermalhydraulics, physics, passive safety, fuel, safeguards, reactor operations, and materials research
- Initial efforts were on technology agnostic research but shifting towards targeted research

Government R&D Funding Opportunities

- NRCan Enabling SMR Program: R&D to address waste generated from SMRs and to develop Canadian supply chains for SMR manufacturing and SMR fuel supply.
- NRCan-NSERC Partnership Program
- NSERC-CNSC Small Modular Reactors Research Grant Initiative

Education

UNENE – University Network of Excellence in Nuclear Engineering



The network advances ***nuclear knowledge***, builds ***capacity*** and heightens ***visibility*** of Canada's university excellence

Stronger together for Canadian innovation

UNENE is a network of Canadian universities, industry, government and international institutions dedicated to excellence in nuclear science, technology and engineering

With its **partners** and **funding organizations**, UNENE works to advance nuclear knowledge, build capacity and heighten visibility of Canada's strength as a global partner, and to elevate the role of nuclear in advancing global sustainability, prosperity and a clean energy

University Members

- University of New Brunswick
- McMaster University
- Ontario Tech University
- Queen's University
- Royal Miliary College of Canada
- University of Guelph
- University of Toronto
- University of Waterloo
- University of Windsor
- Western University
- University of Regina
- University of Saskatchewan
- Polytechnique Montreal
- International University Member Universitatea Politehnica din Bucuresti

Industry Members

- Bruce Power
- CANDU Owers Group
- Kinectrics
- Nuclear Waste Management Organization (NWMO)
- Ontario Power Generation
- Atkins-Réalis
- Clean Core Thorium Energy

Government Members

- Natural Resources Canada
- Canadian Nuclear Safety Commission
- Canadian Nuclear Laboratories

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Canada’s Nuclear R&D Infrastructure to Support SMRs & Advanced Reactors

AECL/CNL

More than 50 unique facilities and labs, several licensed nuclear facilities

- Materials & fuels testing and characterization (active and in-active)
- Corrosion loops
- Safety & thermalhydraulics
- QA Program

CanmetMATERIALS

Core strengths: Materials science & unique facilities

- Advanced electron microscopy
- Corrosion assessment
- Stress corrosion cracking/corrosion fatigue
- Materials property assessment
- Alloy development

Kinectrics

Global Organization

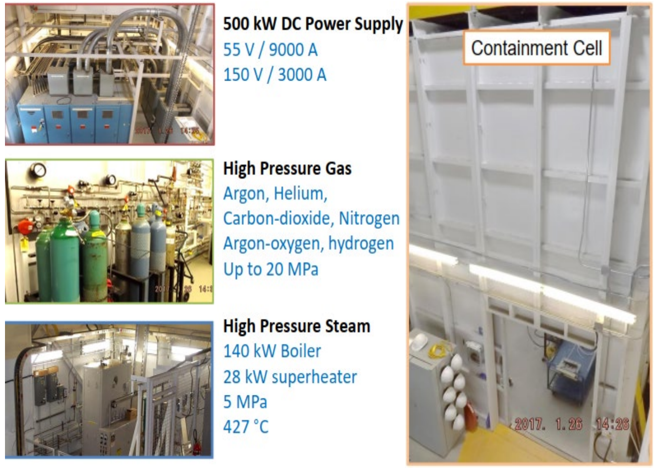
- Ontario Hydro Research – precursor to Kinectrics
- Licensed facilities
- Material & nuclear component testing
- Nuclear Engineering design
- Licensing & Safety
- QA Program

www.kinectrics.com

(Some of) CNL's Unique Facilities

Advanced Nuclear Materials Research Centre (under construction)

- 125,000 square foot space
- 12 hot cells and 23 laboratories
- Will complement current hot cell facilities dating back to the 1950s



500 kW DC Power Supply
55 V / 9000 A
150 V / 3000 A

High Pressure Gas
Argon, Helium,
Carbon-dioxide, Nitrogen
Argon-oxygen, hydrogen
Up to 20 MPa

High Pressure Steam
140 kW Boiler
28 kW superheater
5 MPa
427 °C

High Temperature Fuel Channel Laboratory

- Heat transport systems under postulated accident scenarios involving insufficient primary and/or secondary emergency cooling

Thermalhydraulics Laboratory

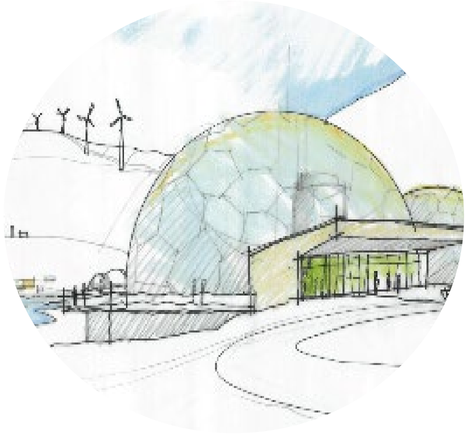
- Single, two-phase, multicomponent flow and heat transfer

- Natural and forced circulation
Simple and complex geometries
up to 1.7 MW power

How CNL is Enabling SMRs & Advanced Reactors

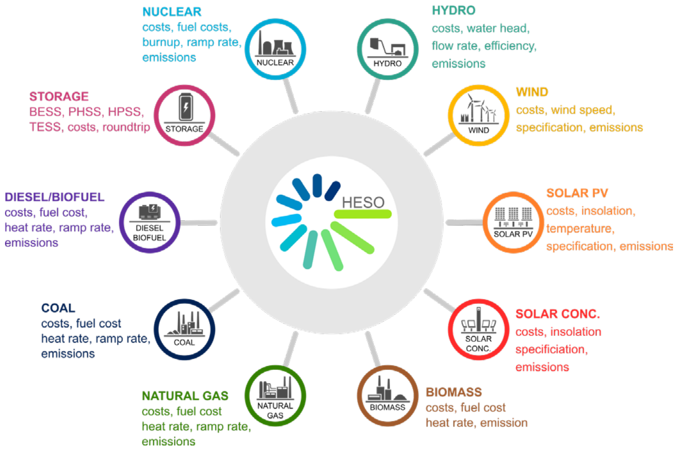
SMR Demonstration Siting

Hosting a demonstration SMR on a CNL-managed site



Clean Energy, Demonstration, Innovation, and Research (CEDIR) Initiative

Advancing technology readiness via a demonstration platform for clean energy systems and adjacent technologies



Hybrid Energy System Optimisation (HESO)

Advancing knowledge through modelling, simulations, and experiments

USNC's vision of its MMR concept - https://www.world-nuclear-news.org/

Canadian Nuclear Research Initiative (CNRI)

Working with commercial companies to apply CNL's nuclear capabilities to technical challenges

Fuel, physics, environment, reactor operations, safeguards, and materials

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Irradiation Facilities

RMTL
Queen's University

Queens University Reactor Materials Testing Lab

- Accelerator to emulate irradiation damage / transmutation
- Combined irradiation damage and stress
- Combined irradiation damage and environment

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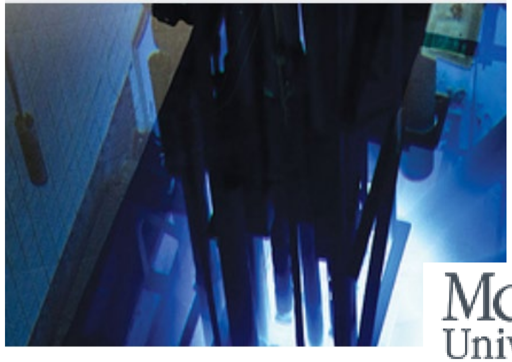
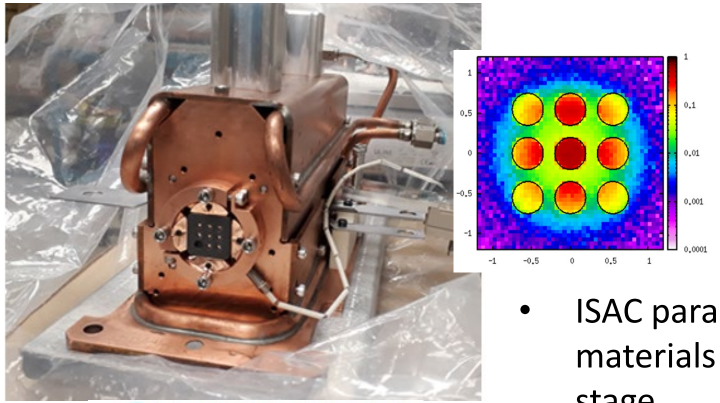


McMaster University

McMaster Nuclear Reactor & Centre for Advanced Nuclear Systems

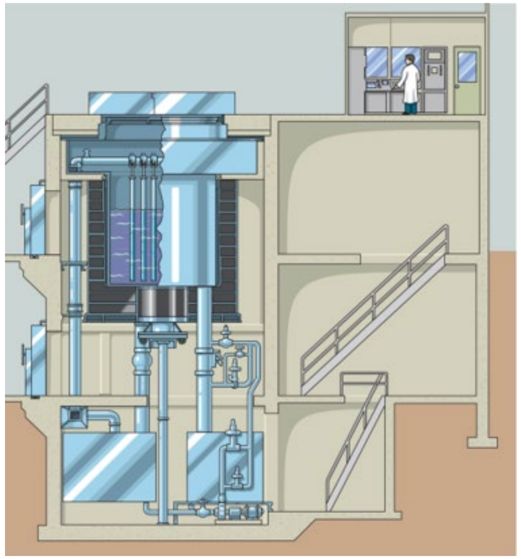
- **MNR** - 3 MW with a maximum thermal neutron flux of 1×10^{14} n/cm^{2}s, open-pool type Materials Test Reactor
- **CANS** - a suite of post irradiation examination capabilities and new test equipment
- **High Level Laboratory Facility** - CNSC licensed laboratories with hot cells and equipment capable of handling highly radioactive materials
- **Cyclotron facility, Accelerator lab**



TRIUMF

TRIUMF - Canada's Particle Accelerator Centre

- ISAC parasitic materials irradiation stage
- 500 MeV with intensity of proton beam between 4×10^2 to 4×10^7 protons/cm^2/s.



CNL Zero Energy Deuterium Reactor

- Zero power heavy water moderated tank-type reactor
- **Power:** up to ~200 W (thermal)
- **Flexibility:** operate with new fuels/coolants/materials as required

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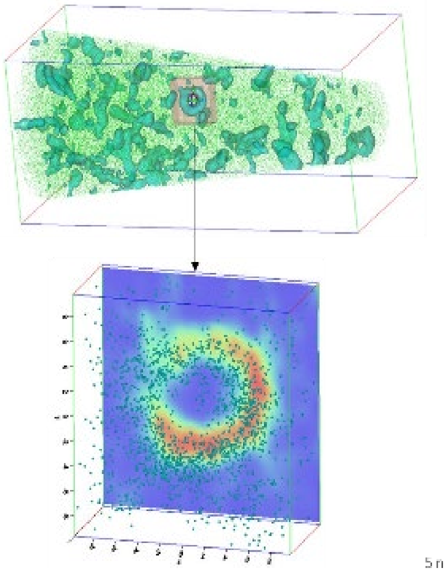
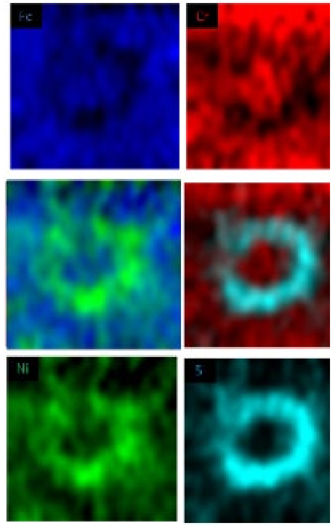
Characterization Facilities

McMaster University





McMaster University Canadian Centre for Electron Microscopy

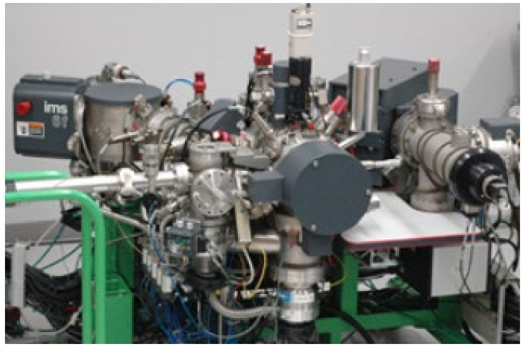
Canadian Light Source

Canadian Light Source | Centre canadien de rayonnement synchrotron

- Canada’s synchrotron
- X-ray imaging has proven extremely useful for imaging the microstructure of composite materials
- Faster than conventional techniques
- *In-situ* imaging of defects, damage, stress

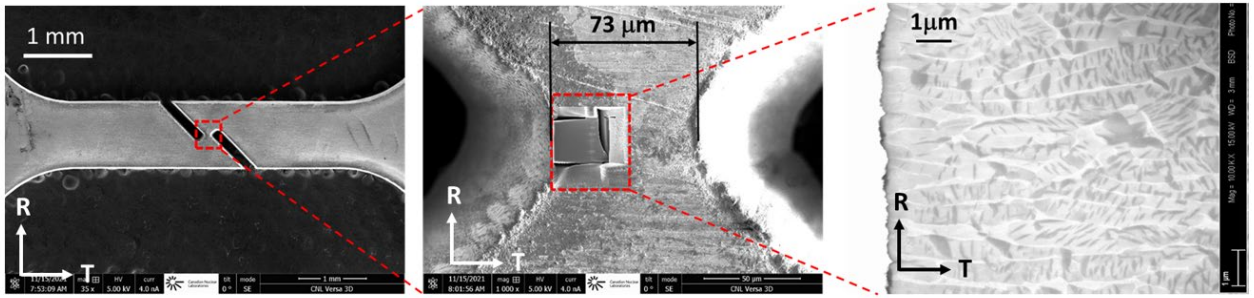
SURFACESCIENCEWESTERN

Western UNIVERSITY · CANADA



CNL – Laser Fabrication and Characterization

- Precision small-scale mechanical test specimens including neutron irradiated specimens



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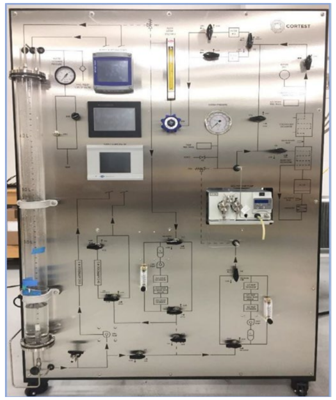
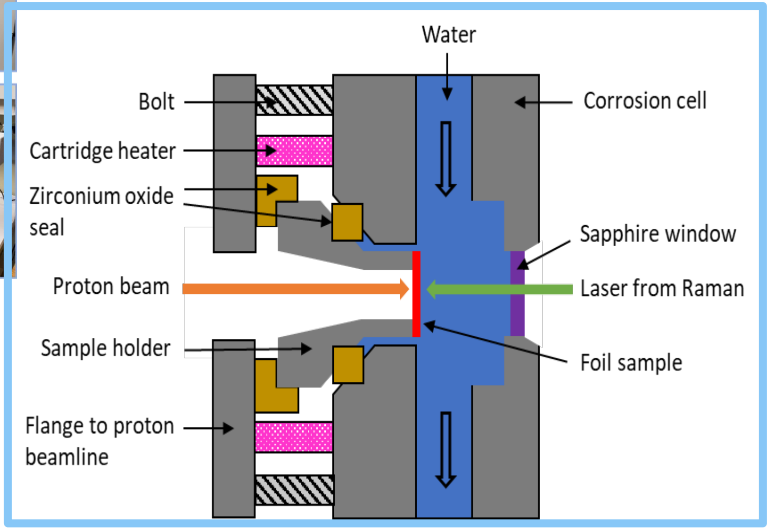
Corrosion Facilities



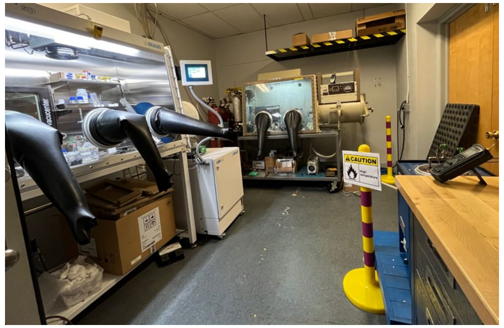


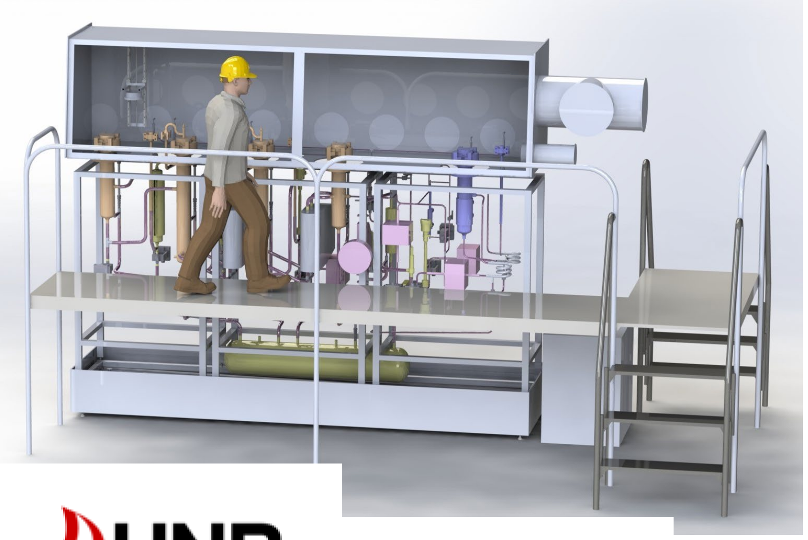
RMTL

Queen's University

Queen's In-situ Irradiation Corrosion Facility

- Combined irradiation damage and environment, in situ irradiation-corrosion





UNB EST. 1785 UNIVERSITY OF NEW BRUNSWICK

CNER Centre for Nuclear Energy Research

University of New Brunswick Centre for Nuclear Energy Research

- Water chemistry control and corrosion detection, monitoring
- Eight registered high-pressure/temperature water loops
- Full suite of surface science analysis and analytical chemistry

UNB-CNER Advanced Nuclear Reactors Laboratory:

- New molten salt lab under construction:
  - Glovebox facilities for salt preparation and quantification
  - Thermal and physical property measurements
  - Corrosion assessment
- New sodium lab and test loop

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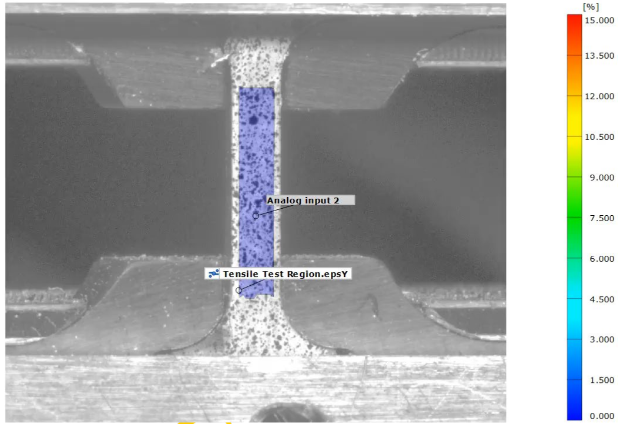
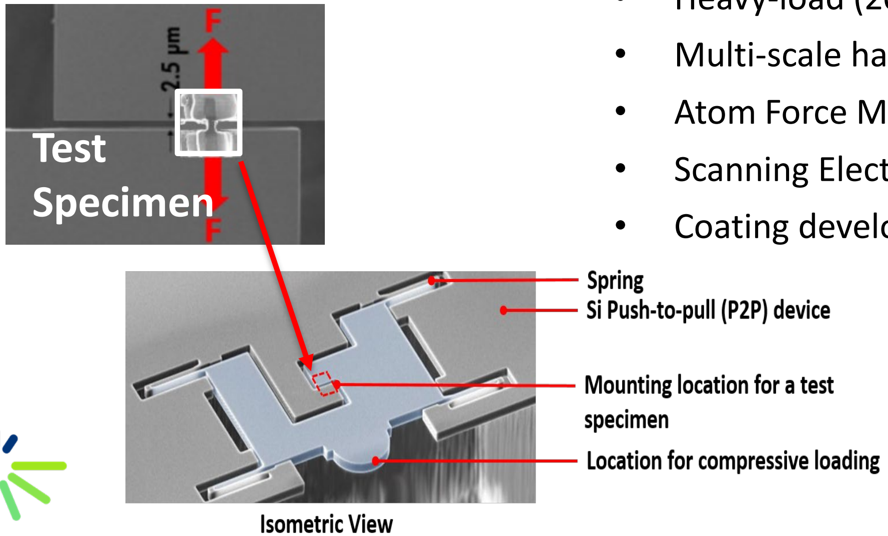
Mechanical Property Assessment

- Charpy impact
- Drop weight tear
- Tensile/Compression
- Fracture mechanics
- Creep and Fatigue up to 950 °C
- Stress and/or strain controlled
- Rotating bend
- Multi-scale mechanical testing (micro-to-bulk), tensile, fracture toughness
- High Temperature (850°C) nano-indentation (ex-situ & in-situ)

Canada
Natural Resources Canada





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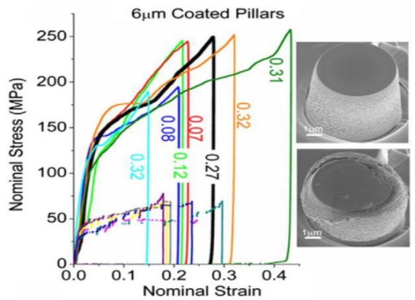
McMaster University

Materials Property Assessment Lab

- Nano/micro-scale indentation, scratch, impact, fatigue (-30 to 1200°C)
- Micro and macro scratch & wear testing for coating adhesion
- Tribometer – Industry standard for measuring friction, wear & lubrication
- Heavy-load (2000N), HT (1000°C) tribometer
- HT Universal Testing System
  - -70°C to 1500°C
  - Loads up to 250 kN
- Heavy-load (2000N), HT (1000°C) tribometer
- Multi-scale hardness tester (10g – 60kg)
- Atom Force Microscope
- Scanning Electron Microscope, Optical Microscopes
- Coating development (hybrid PVD coater) and evaluation

MPAL
Materials Property Assessment Laboratory



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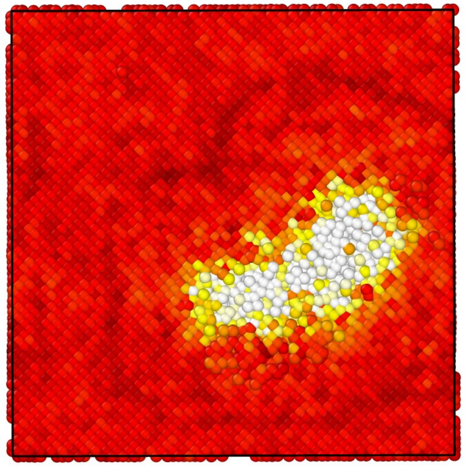
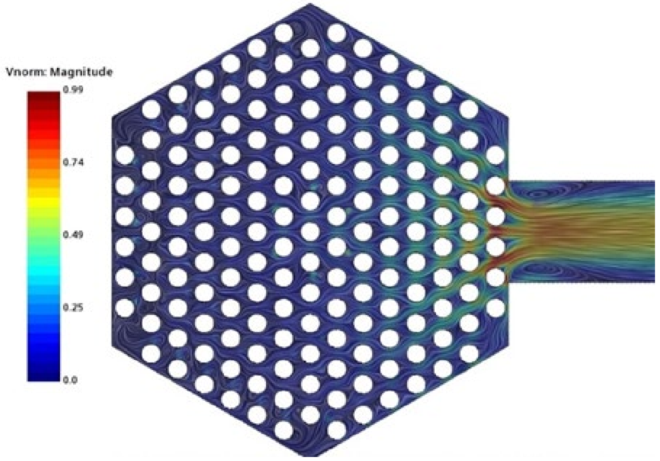
Modelling



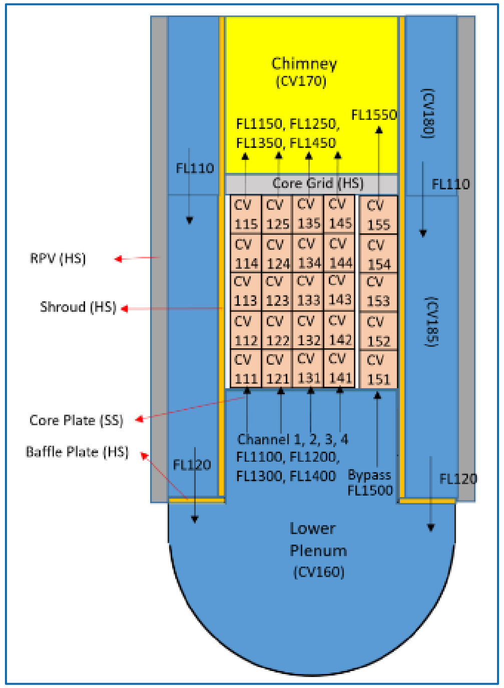
Multi-Scale Materials

- Primary defect production atom-by-atom
- Predict (transmutation) He bubble nucleation and growth
- Nearly-unique ability to simulate aging over timescales of ~seconds with atomistic resolution (accelerated dynamics)



Development of Coupled Code Suite for SMRs

- CNL is developing multi-physics modelling capabilities for modelling non-water cooled SMR concepts
- Coupled code suite included three disciplines: CFD, System TH and Neutronics
- Collaboration with US-DOE
- Development of TH (ARIANT) and Physics (OpenMC) codes for SMR applications



Severe Accident Modelling

- Modelling of various generic SMR designs using the MELCOR code
- Water-cooled (iPWR, small BWR) and advanced (HTGR, and soon SFR)

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Queen's University

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

OntarioTech University

Western University · Canada

Fuel Fabrication & Advanced Materials Development

CNL - Fuel Fabrication

- Conventional fuel fabrication processes
- Advanced fuel fabrication methods (SPS)
- Advanced manufacturing techniques, 3D printing of uranium and thorium filament materials

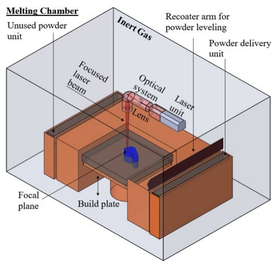
Queens - ODS Ni-based alloys

- $Ni\text{-}15Cr\text{-}4Al\text{-}3W\text{-}0.8Hf\text{-}1Y_2O_3$
- HIP: 1100°C, 4hr, 140 MPa
- Heat Treatment
  - Solution heat treated: 1100°C, 4hr, a/c
  - Aging: 800°C, 3hr, a/c

CMAT – Vintage HT-9 and HEAs

- Alloy was tested in EBR-II in liquid sodium fuel
- Potential fuel cladding for SFR
- Very difficult to process to avoid delta phase formation
- Collaboration with CNL to develop HEAs FeCrMnNi – irradiation & mechanical testing

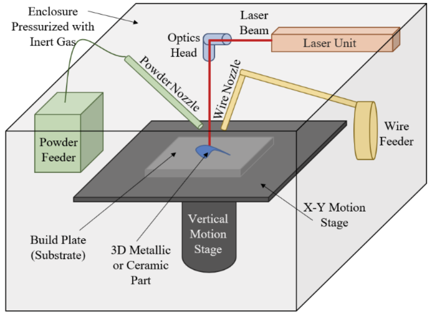
Powder Bed Fusion



Heat source:
Laser or Electron Beam

Directed Energy Deposition

Feedstock:



Heat source:
Laser or Electron Beam or Gas Arc

Alberta Next-Generation Additive Manufacturing Research Laboratory

- Collaboration to develop high-temperature corrosion-resistant functionally graded material structures fabricated using state-of-the-art additive manufacturing solutions

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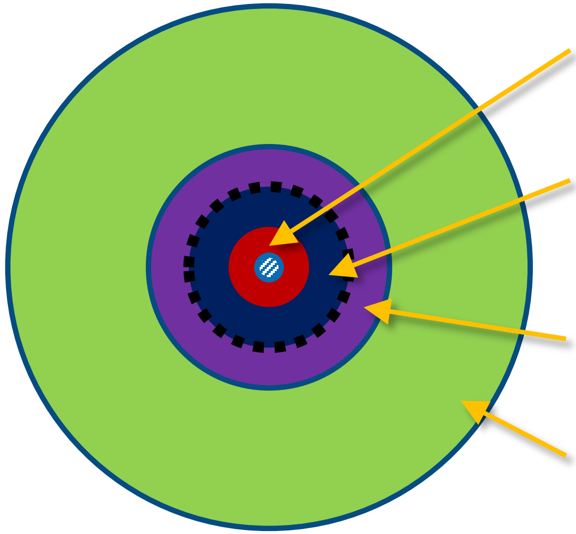
Safety & Security

Cyber Security for Remote SMRs and Wireless Sensor Networks

State-of-the-art, safe, secure and **realistic** cyber security research, training and exercise environment for nuclear and other critical infrastructure.
Representative physical separation for incident response exercises:

- nuclear security operators
- field operations & maintenance
- control room operations
- cyber security operations
- lead controllers/evaluators, and observers

SMR Emergency Planning and Response Optimization



Automatic Action Zone (AAZ): Aim to prevent deterministic health effects.
(IAEA analog is precautionary action zone, PAZ)

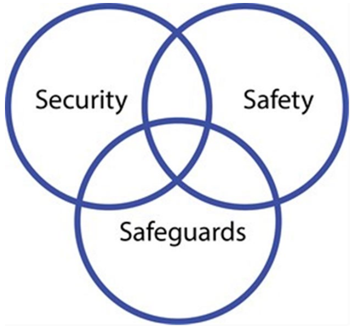
Detailed Planning Zone (DPZ): Aim to reduce stochastic health effects.
(IAEA analog is urgent action zone, UPZ)

▪▪▪▪▪▪▪ Limit of "EPZ" per IAEA definition ▪▪▪▪▪▪▪

Contingency Planning Zone (CPZ): Aim to reduce chance of exposure.
(IAEA analog is extended planning distance, EPD)

Ingestion Planning Zone (IPZ): Aim to restrict the distribution of potentially contaminated products.
(IAEA analog is ingestion and commodities planning distance, ICPD)

Proliferation Resistance and Physical Protection



- Safety & security (sabotage)
- Safety & safeguards (diversion, misuse)
- Safeguards & security (theft)

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How Canada is Enabling SMRs & Advanced Reactors

International Collaborations – GIF, NEA, IAEA, EU

SCWR

- System Steering Committee
- Thermalhydraulics & Safety
- Materials & Chemistry

MSR

- Provisional System Steering Committee
- Fuel & Coolant Salt Chemistry
- System Integration PA

VHTR

- System Steering Committee
- Materials
- Hydrogen
- Fuel and Fuel Cycles (observer)
- Computational Methods Validation and Benchmarks (observer)

NEA Working Groups

- Economic Modelling, Proliferation Resistance and Physical Protection,
- Risk and Safety and, Advanced Manufacturing and Material Engineering Task Non-Electric Applications of Nuclear Heat Task Force

IAEA Contributions

- Co-Authors of TECDOCs under review
- Participating/Leading new CRPs
- NHSI - Industry Track

Bi-Laterals

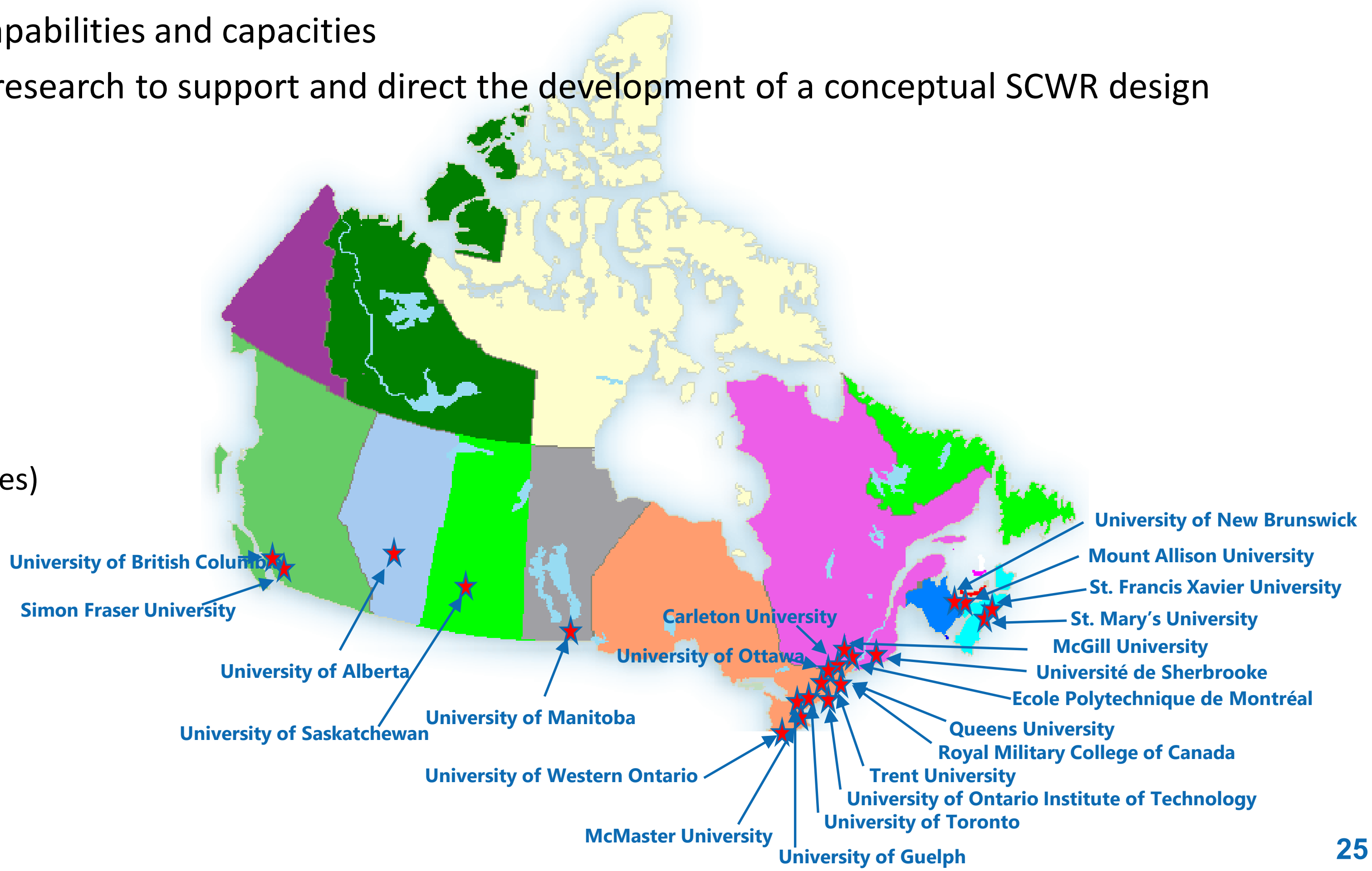
- Canada - US; Canada - UK
- AECL and CNL MOUs with laboratories and academia

Canada’s Gen IV National Program

Officially launched in 2006

- Development of SCWR systems through participation in GIF multilateral R&D collaborations
- R&D for non-greenhouse-gas-emitting hydrogen production technologies using nuclear energy
- Establishment of new national capabilities and capacities
- Undertaking basic/fundamental research to support and direct the development of a conceptual SCWR design

- 22 Participating Universities – 9 Provinces
- 5 Federal Laboratories (CNL, NRCan, NRC)
- Over 800 presentations and conference proceedings
- Over 300 technical reports
- Over 350 peer-reviewed publications
- Over 400 HQP trained 5 patents
- New facilities (Universities & Federal Laboratories)
- Enhancing the R&D capabilities of federal laboratories and universities
- Development of databases and models
- International Collaborations – GIF participants



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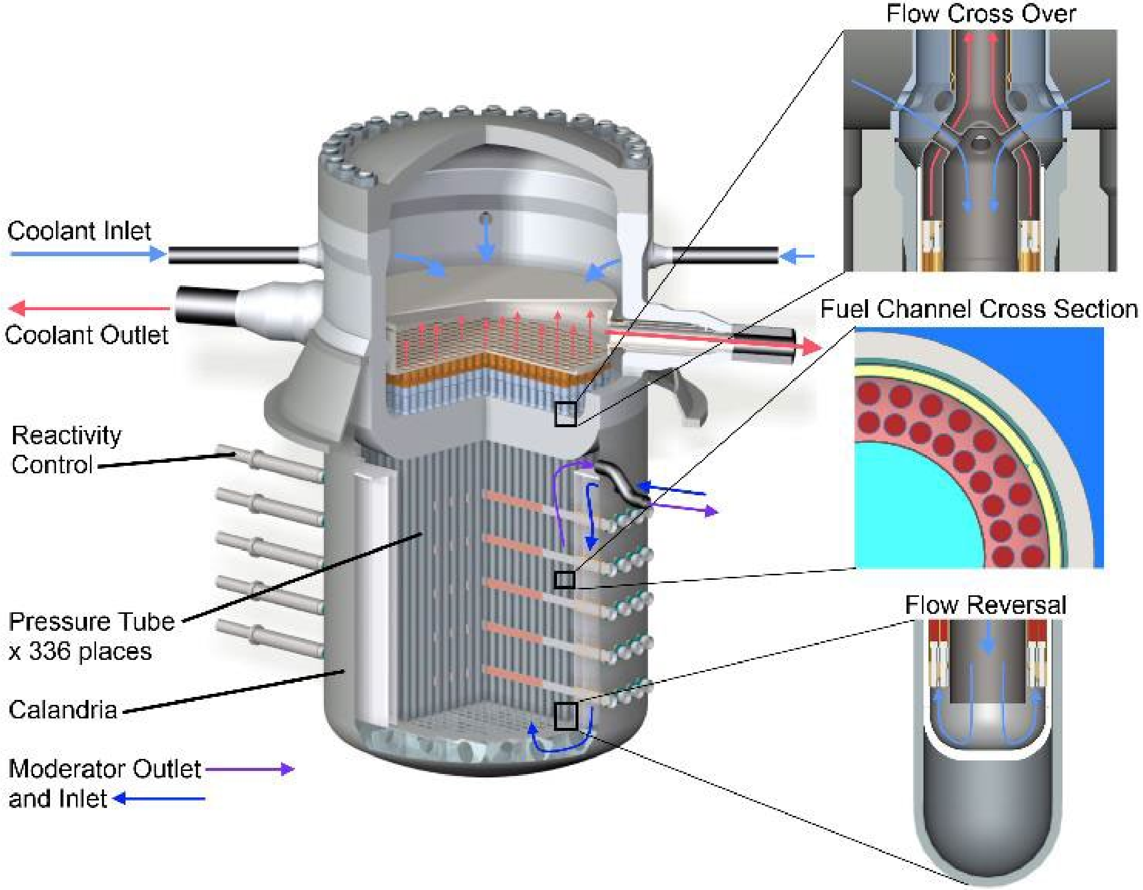
Wealth of knowledge developed through modelling and experiments

Canadian SCWR Concept Schematic



- **Grid Power =** ~1200 MWe
- **Operating Life** = 75 Years
- **Direct cycle –** No steam generators, no steam separators
- **336 fuel channels at 25 MPa**
  - Inlet temperature at 350 °C
  - Outlet temperature at 625 °C
- **Fuel channels**
  - Zirconium alloy pressure tube
  - Zirconia insulator
- **Inside diameter = 5.5 m**
- **Low-pressure calandria at ~0.3 MPa**
- **Thorium-13%Plutonium fuel (Ref),**
  - Enriched UO_2 fuel is possible.

Super Critical Water-Cooled Reactor Summary

Thermalhydraulics & Safety

- Subchannel analysis
- CFD
- Flow instability
- Heat transfer and hydraulic resistance under SC conditions
- Safety analysis

Materials

- Pressure boundary system design
- Corrosion of cladding materials
- Coupling of fluid mechanics, thermodynamics of reactions and mass transfer with corrosion

Mechanical components

- FE analysis
- Mechanical design
- Joining techniques such as co-extrusion and friction welding
- Heat transfer through complex geometries
- 3D printing of advanced metallic insulators

Reactor Physics

Full core analysis using Monte-Carlo method

Fuel & Fuel Assembly

- Welding techniques
- Reference fuel selected to GIF goals (sustainability and non-proliferation)

Economics

Modelling using G4ECONS software

Multidisciplinary Approach for SCWR R&D

COST EFFECTIVE !!!

Nuclear Fuel

Moderator

Coolant

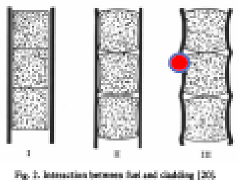
SELECTION of CLADDING MATERIAL

ITERATIVE PROCESS

MATERIAL SELECTION

Mechanically resistant at high temperatures (normal and accident)

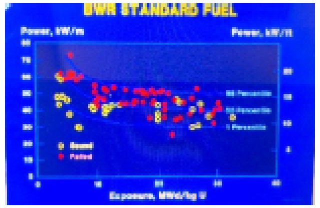
Mechanical interaction between fuel and cladding:
-Cladding creep
-Fission gases/swelling



Stresses/
strains/
hot spots

Fig. 2. Interaction between fuel and cladding [20].

Steinar Nuclear Engineering and Design 21 (1972) 237-256.



PCI failures (red) ocurred with an increasing probability as the maximum ramp power increased, (Armijo/Abdullahi, 2009)

Corrosion resistance

Chemically stable

Oxidation of cladding (0,17 times the cladding thickness; 0,6 mm)

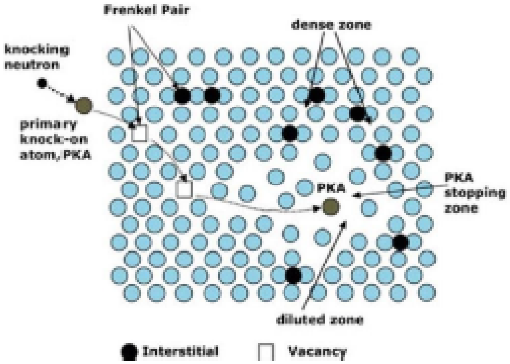
Release of corrosion products/Thermal cond.

Stress corrosion Cracking (SCC)

Neutron resistance (defects tan modifies corrosion res., mechanical properties, difussion….) and high neutron transparency

Low neutron absorption cross section

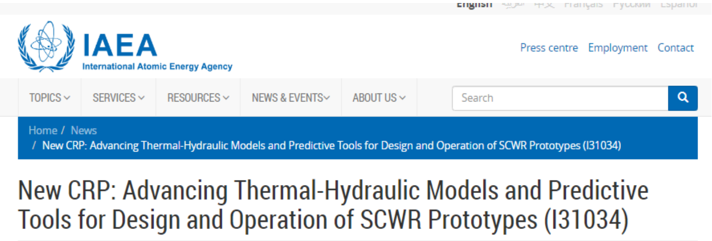
Thermal expansion/Thermal conductivity



Thermalhydraulics and Safety

- Several international collaborations working on SCWRs R&D
  - GIF SCWR Thermalhydraulics and Safety PMB
  - ECC-SMART Project
  - IAEA CRP
- Close knowledge gaps and provide basis for the prototyping of SCWRs
- Heat transfer and hydraulic resistance under SC conditions, flow instability, CHF near the critical point

ECC smart



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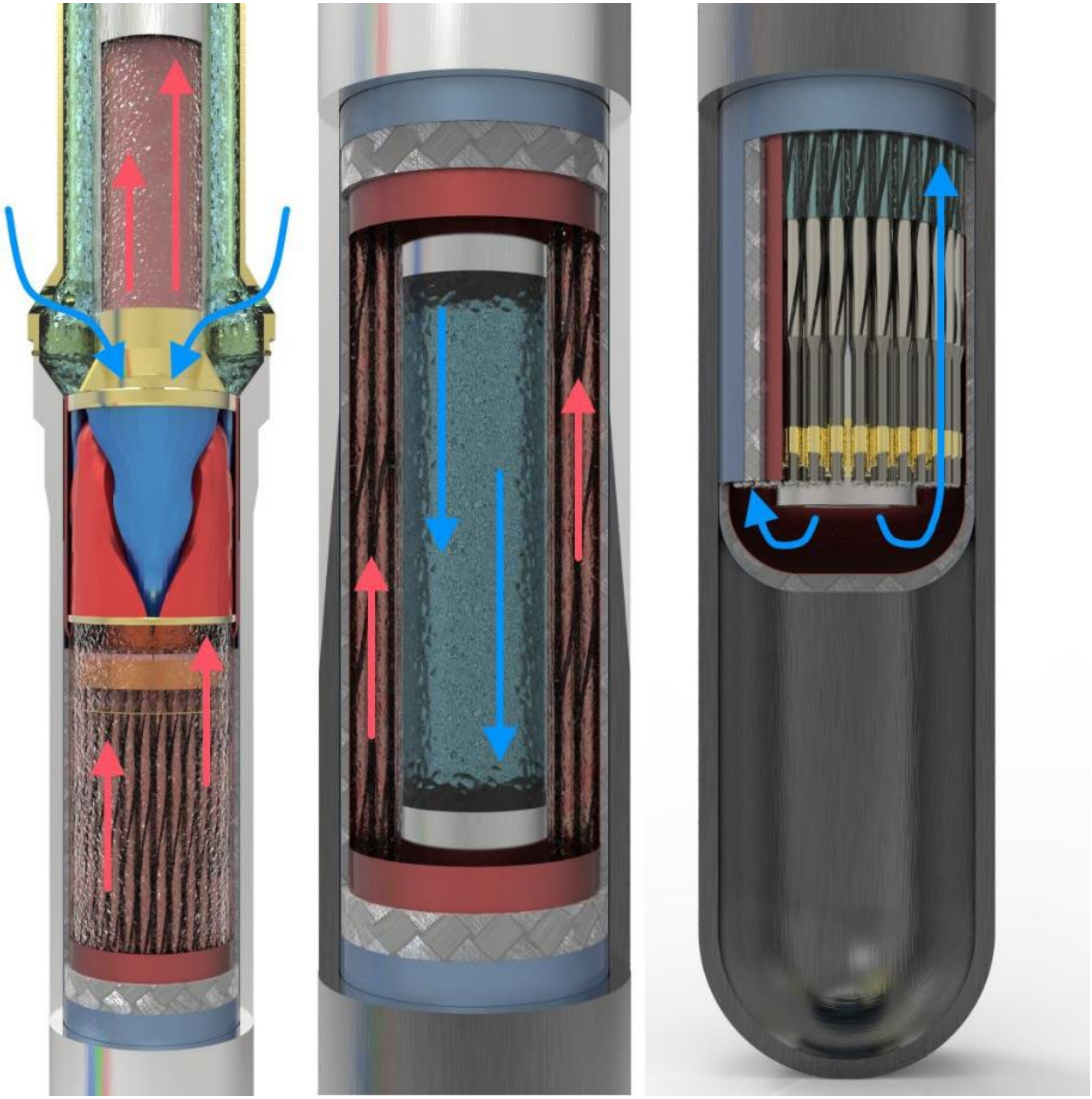
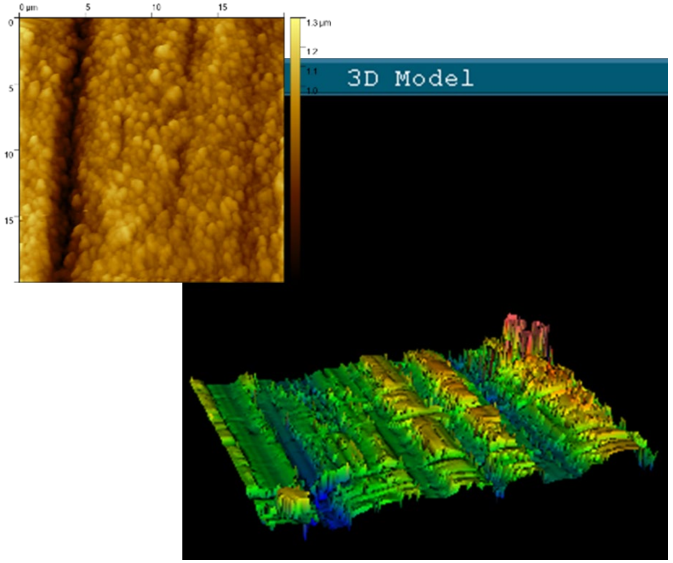
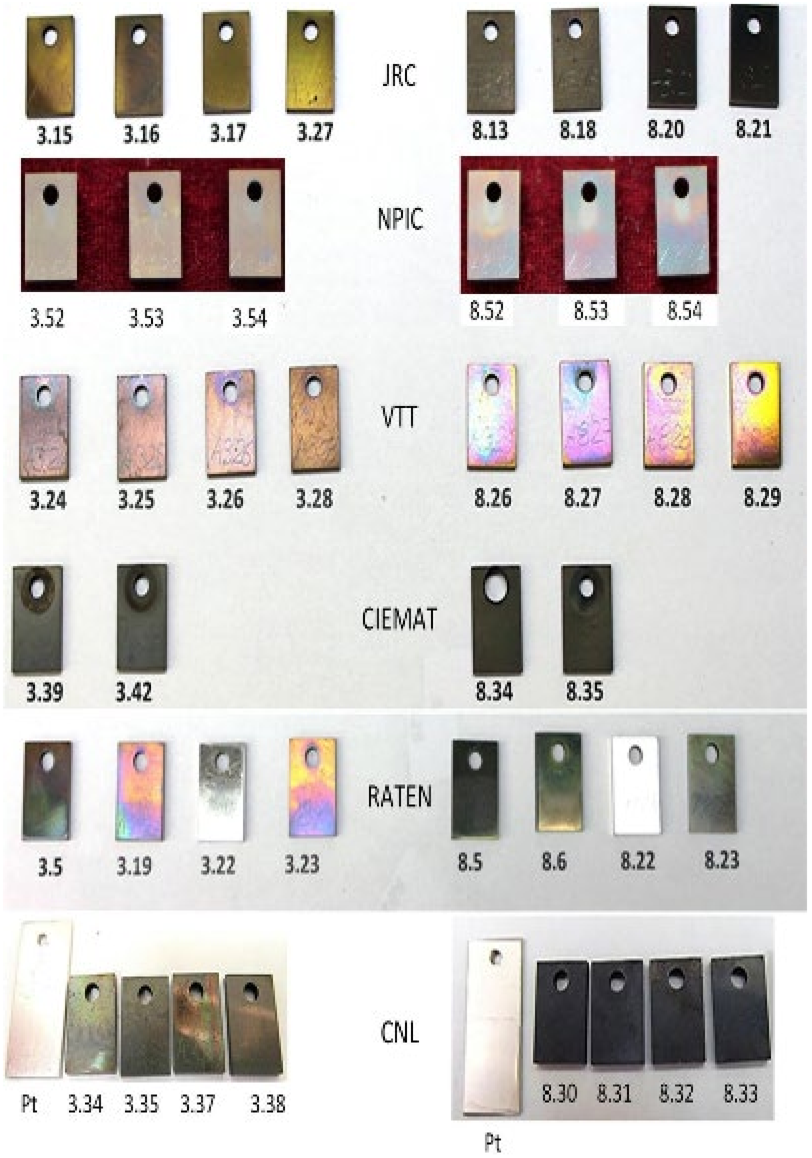
New CRP: Advancing Thermal-Hydraulic Models and Predictive Tools for Design and Operation of SCWR Prototypes (I31034)



Materials and Chemistry

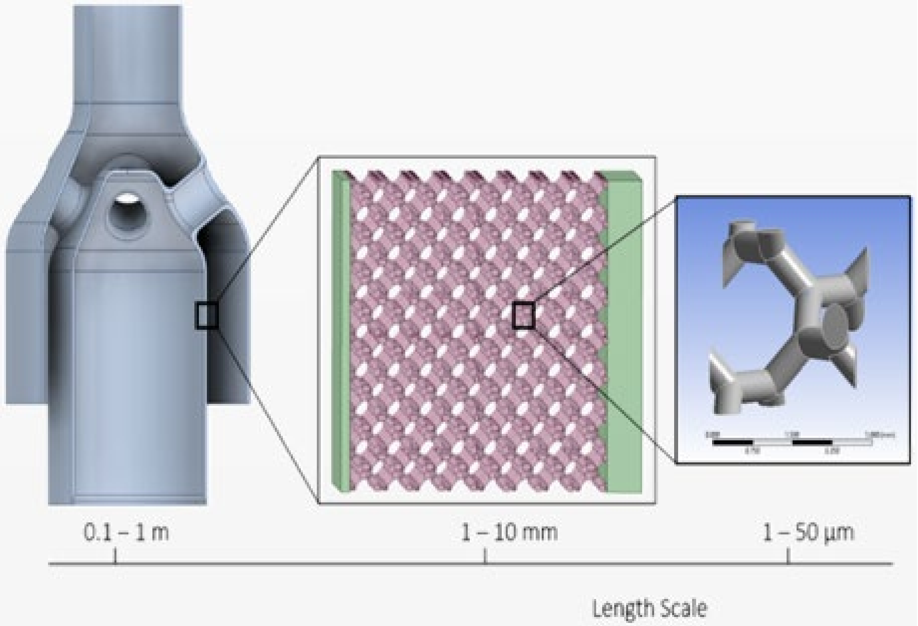
- Long-term exposure of cladding candidates to supercritical water conditions
- Large database of experimental data. Several domestic and international institutions are contributing to this database
- Performing mechanical, irradiation and oxidation tests on the sample coupons

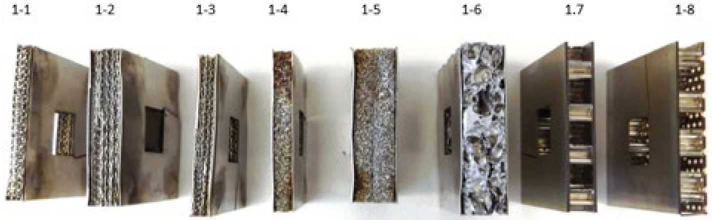




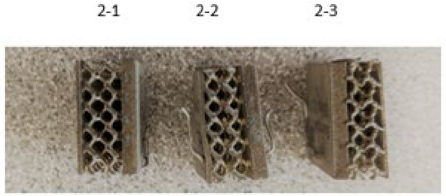
Passive Safety - Conduction

Modified Divided Bar Test Apparatus





Conventionally Manufactured Samples



Additive Manufactured Samples

Measurement of Thermal Conductivity of Metallic Based Insulators

- Samples developed in collaborations between CNL and Canadian universities
- Conventional samples are stainless steel plates with corrugated foam/wire mesh structures
- 3D printed metallic gyroid lattice structure.

Molten Salt Research Summary

Thermophysical Properties

- Salt preparation
- Salt heat capacity via DSC measurements
- Salt thermal diffusivity via laser flash measurements
- Fuel salt synthesis
- Fission project behaviour and release
- Fission product chemistry

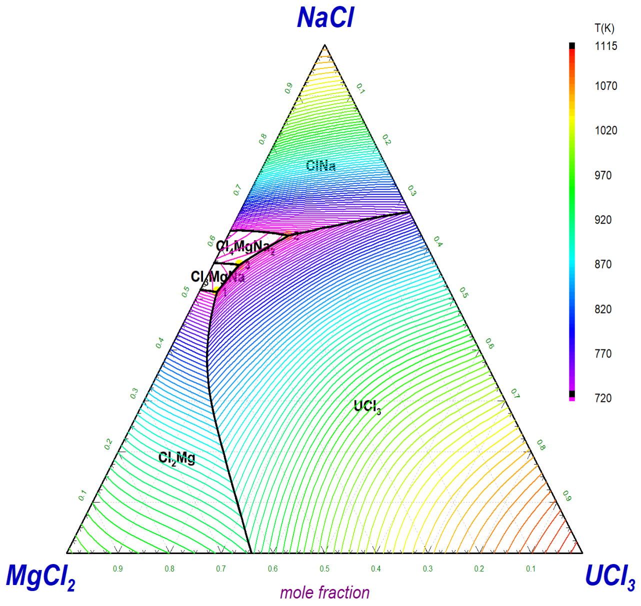
Materials & Corrosion

- Corrosion
- Static and dynamic loops
- Several materials:
  - SS 316
  - Grade 91 steel
  - Hastelloy N
  - Alloy 242
- Activity transport

Thermalhydraulics

- Molten salt natural circulation heat transfer
- Instrumentation testing
- Self-heating fluid testing
- CFD simulations

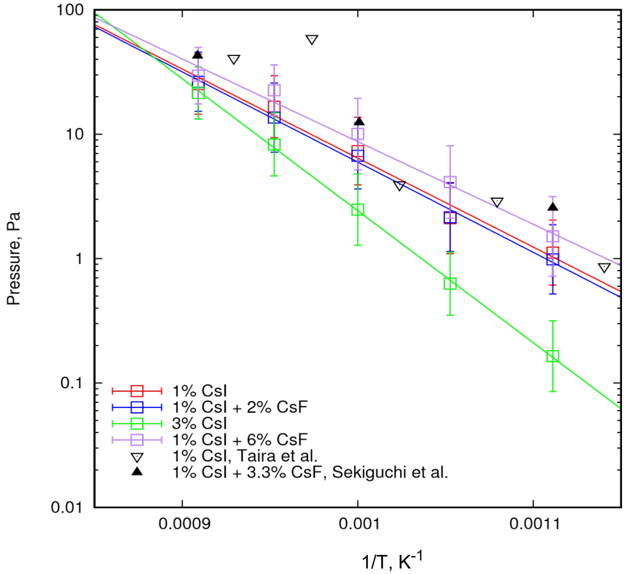
Molten Salt Thermophysical Properties



Experiments & Modelling of Fuel Salts

- Calphad calculations
- Molecular dynamics simulations
- DFT calculations
- Finite Element Analysis

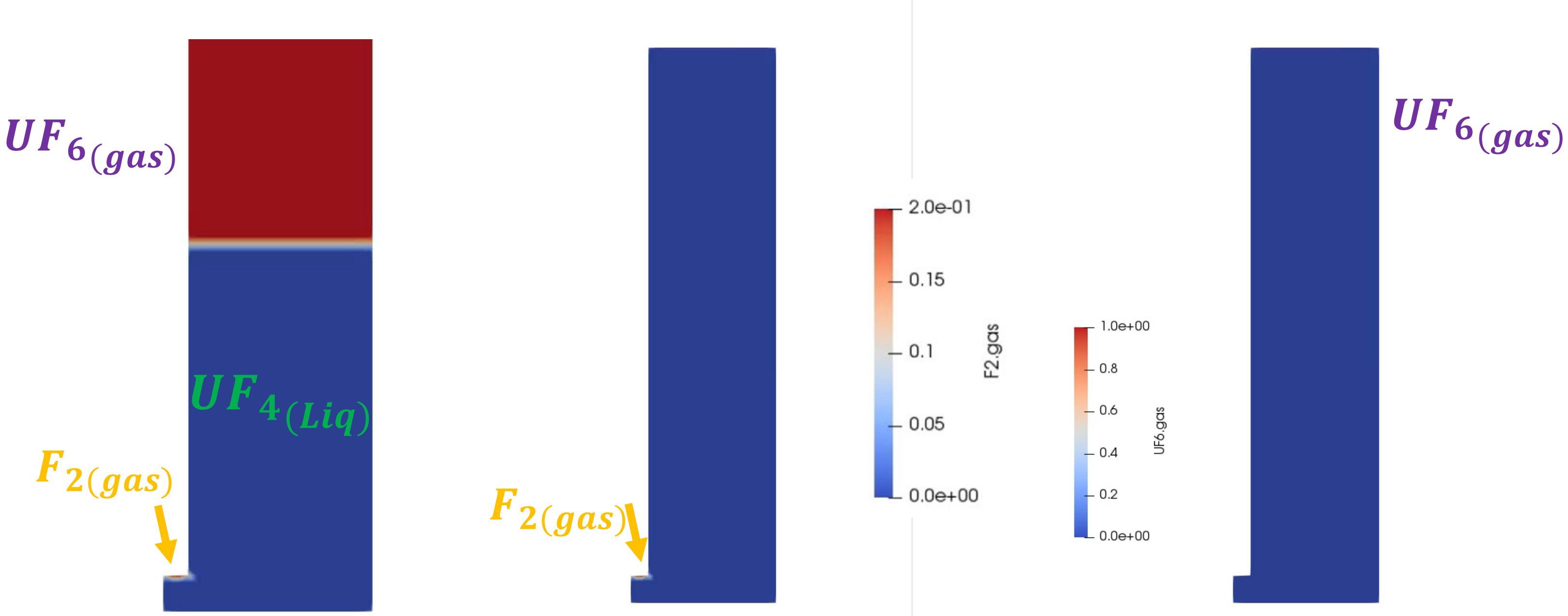
- Fuel-salt synthesis
- Molten salt encapsulation
- High temperature DSC (T_m, C_p, …)
- Laser flash apparatus (thermal diffusivity)
- XRD for phase identification
- TGA for thermal stability
- ICP-OES for composition
- LECO for oxygen analysis



C. Maxwell, *Journal of Nuclear Materials* 563 (2022): 153633

Calculated partial pressure of CsI above FLiNaK with solvated concentrations plotted against inverse temperature.

Molten Salt Thermophysical Properties & Safety



N. Scuro, O. Benes M.H.A. Piro, Annals of Nuclear Energy, in-press (2023).

Fission Product Chemistry

K. Lipkina, K. Palinka, E. Geiger, B.W.N. Fitzpatrick, O.S. Valu, O. Benes, M.H.A. Piro, J. Nucl. Mater., 568 (2022) 153901.

Multi-Physics Simulations

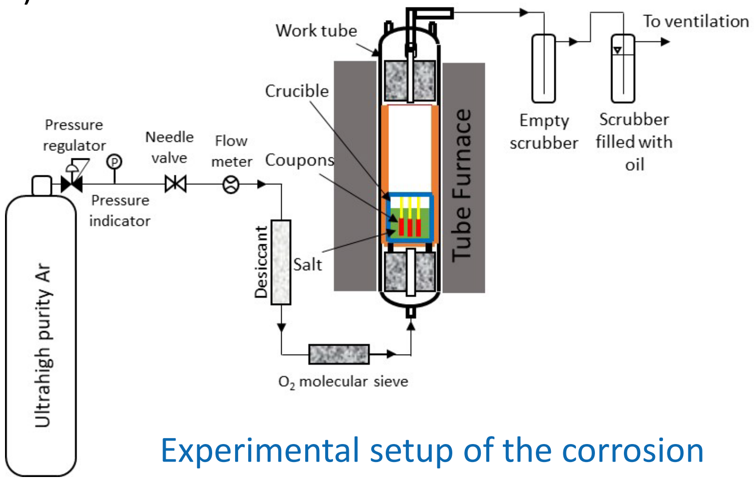
- Coupled CFD with Computational Thermodynamics so that chemically reacting flow with phase transformations could be simulated in an MSR for reactor safety analyses
- Fluorinating gas injected at the bottom of a cylinder containing irradiated fuel salt (i.e., UF4 + coolant + fission products)

https://doi.org/10.1016/j.anucene.2023.110327

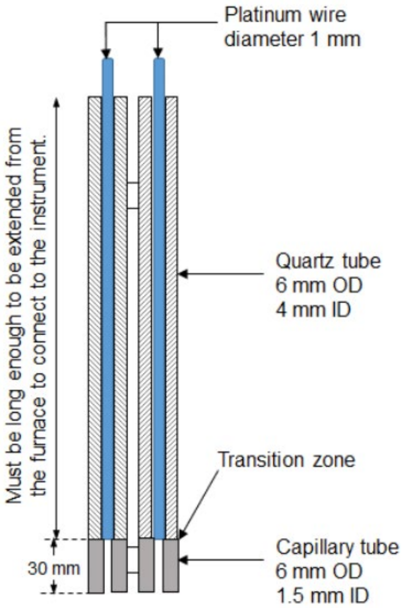
Materials in High Temperature Molten Salt Environment

- **High temperature molten salt corrosion test capability** long-term Demonstration Natural Corrosion Loop operation with rigorously controlled salt chemistry (SS 316L exposed to chloride binary salt mixture)
- Corrosion products released from SS 316L, Alloy 242, and Alloy N at 800 °C were determined in KCl-$MgCl_2$ (61:39 wt%) through **immersion test** (72 h) in Ar
- Development of **electrical conductivity equipment** using Pt-wire probe as electrodes and testing at 550 °C in KCl-LiCl (41-59 mol%)

Methodology for salt sampling, salt chemical analysis, loop decommission and sectioning, characterization of corroded samples and components

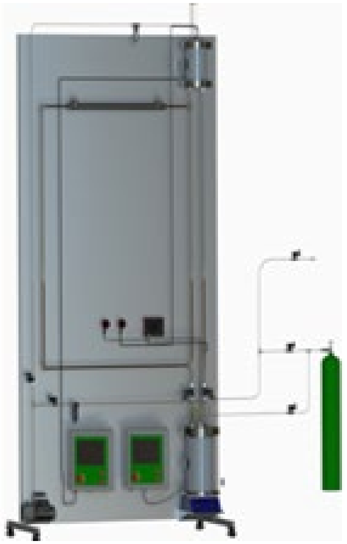


Experimental setup of the corrosion experiment in molten salt



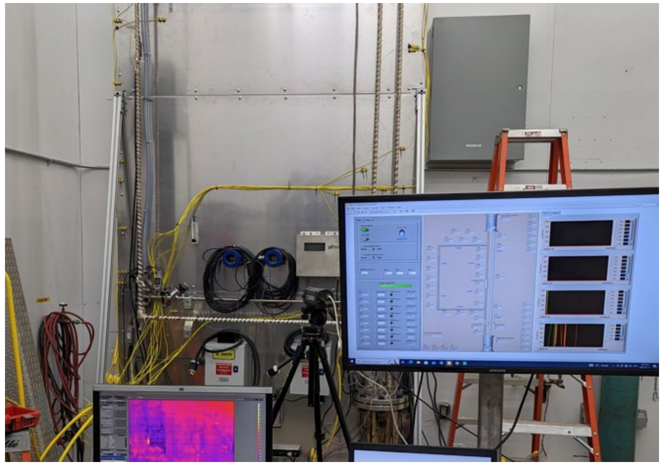
Pt wire-probe

Passive Safety Molten Salt Natural Circulation Heat Transfer Loop



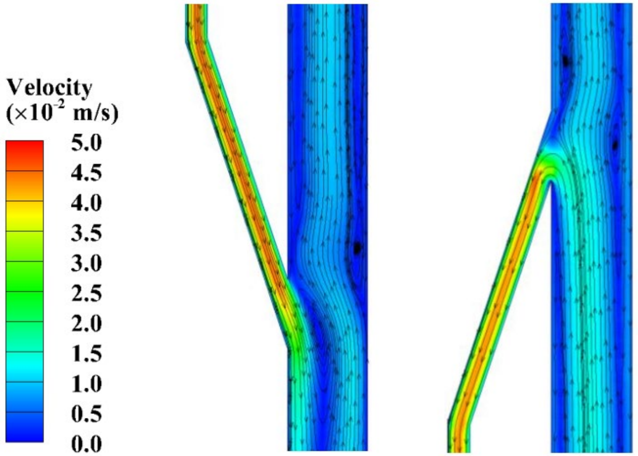
Design

- Simplification of a single loop in the Direct Reactor Auxiliary Cooling System
- Main loop is 2 m tall
- Operate at ~550°C



Construction

- 316 Stainless steel
- Instrumented with fibre-optic sensors, capacitance sensors, thermocouples, ultrasonic flow sensors



ISSN:0029-5639

Testing

- Instrumentation effectiveness
- Changes in geometry due to aging
- Data for benchmarking models e.g. CFD and System Code simulations

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Very/High Temperature Gas Reactor Research Summary

Materials

- Graphite
  - Thermal properties
  - Oxidation
- High temperature materials testing
  - Fatigue
  - Creep
  - Weldments
  - In air and impure He enviroment
- Atomistic modelling
- Corrosion in impure He environment

Thermalhydraulics & Safety

- Passive safety - thermal radiation
- Air ingress experiments
- Severe accident and system thermalhydraulics modeling

Fuel & Fuel Cycles

- Fuel fabrication
- NDE
- Modelling
- Mechanical testing
- Irradiation

Hydrogen

- Cu-Cl Cycle
- High temperature steam & CO_2 electrolysis

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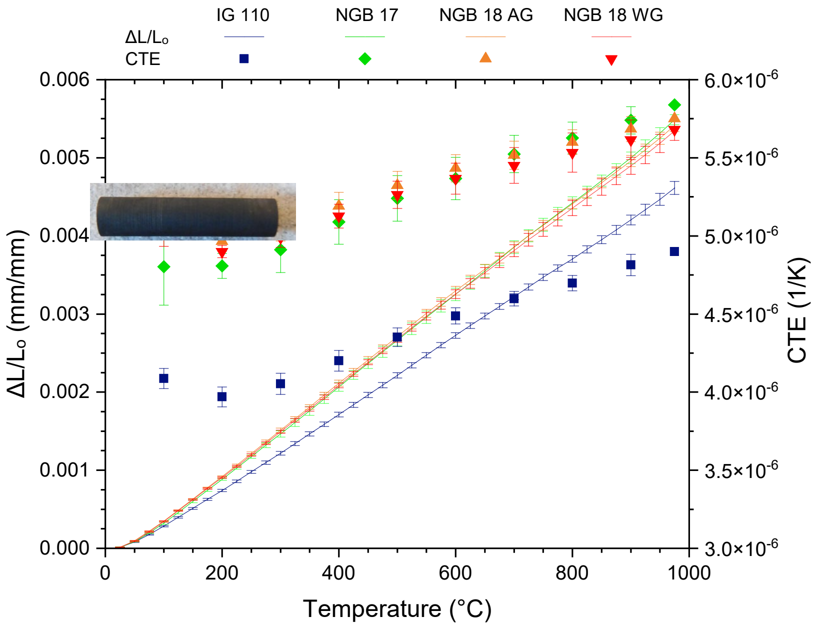
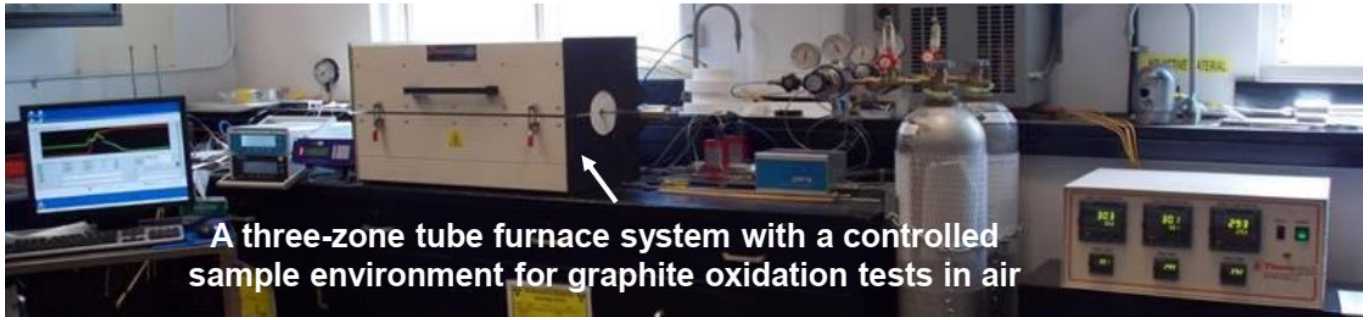
Graphite

Baseline Thermal Properties of Selected Nuclear Grade Pristine Graphite

Thermal Expansion Results

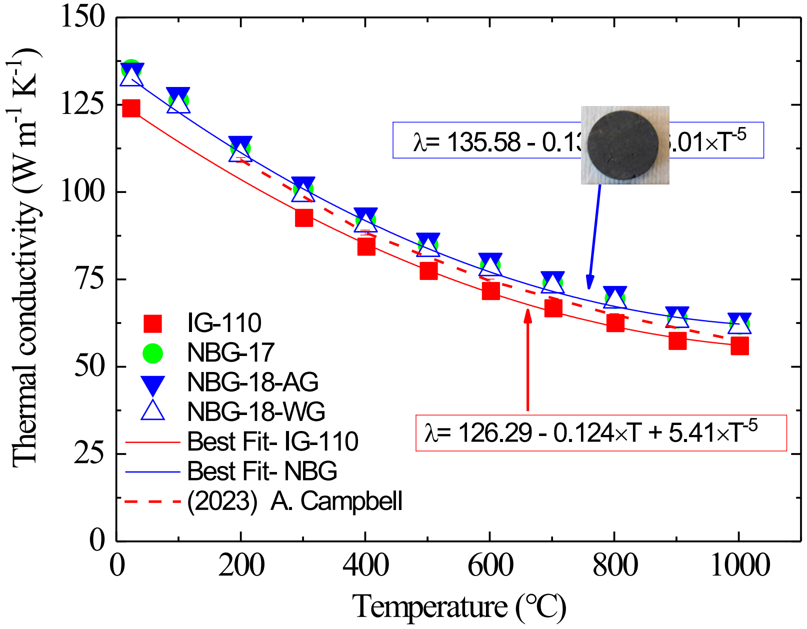


Graphite Oxidation Behaviour



A three-zone tube furnace system with a controlled sample environment for graphite oxidation tests in air

Thermal Conductivity Results



- Thermal properties degradation with oxidation weight loss in air at 550°C
- TGA oxidation experiments of IG-110 & NBG-18
- Thermal oxidation in dry air oxidation at 550 °C in horizontal tube furnace

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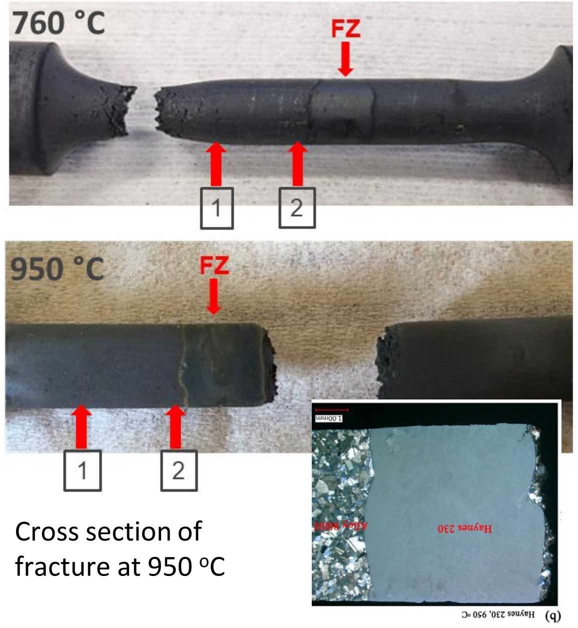
Very High Temperature Materials Testing

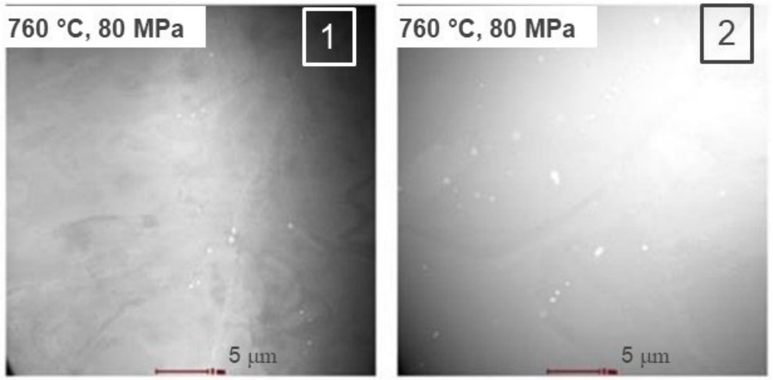
Microstructural Stability and Deformation Mechanisms

Alloy 800H Weldment with Haynes 230 Filler Metal - Microstructure after Creep at 760 and 950 °C



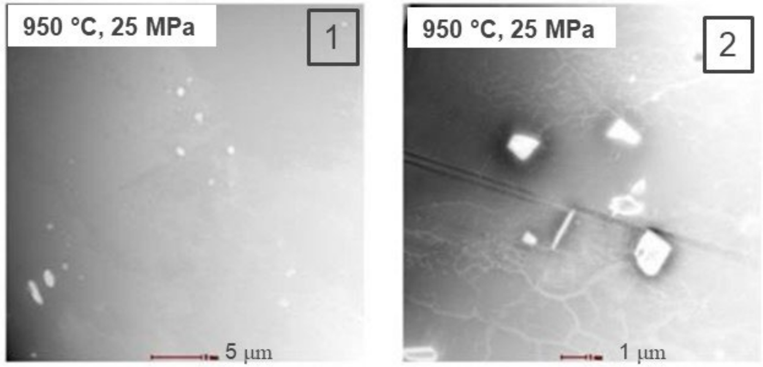
Cross section of fracture at 950 °C

Carbide size increases with higher temperature



Base metal – away from FZ

HAZ – adjacent to FZ



Carbide size increases when closer to the fusion zone

High Temperature (HT) Creep Rigs

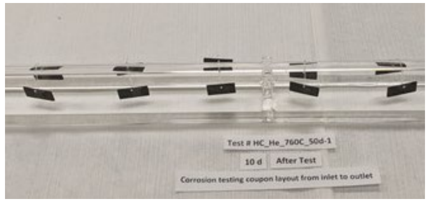
HT Creep Rigs with Environmental Chamber

Corrosion Effects in HTGRs

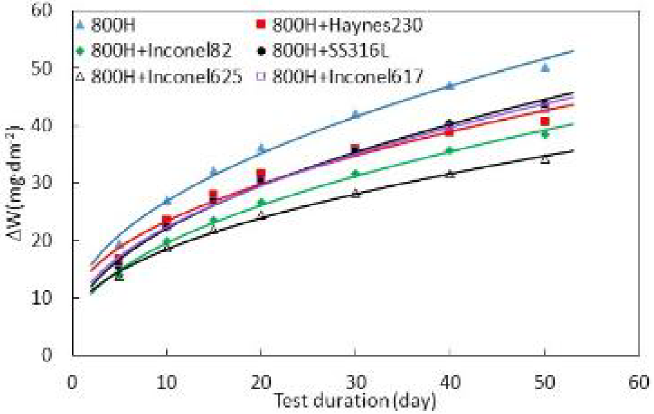
CNL - tests at 760 °C, with purified helium gas, helium gas mixture with 5 ppm H_2O, 50 ppm CH_4 by volume at test duration of 5, 10, 20, 50 days

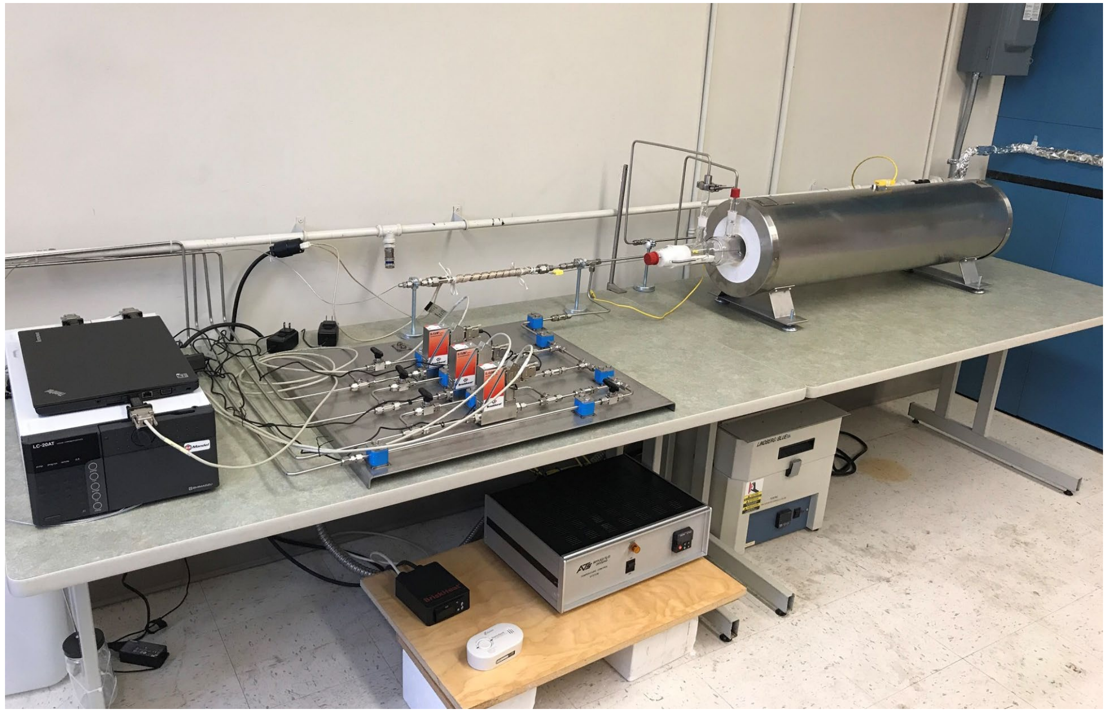
Horizontal quartz-tube furnace

Sample holder and coupons



He with 5 ppm H_2O, 50 ppm CH_4

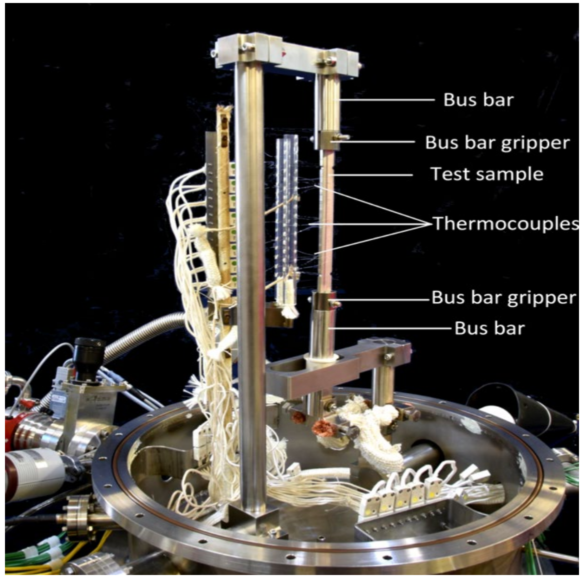




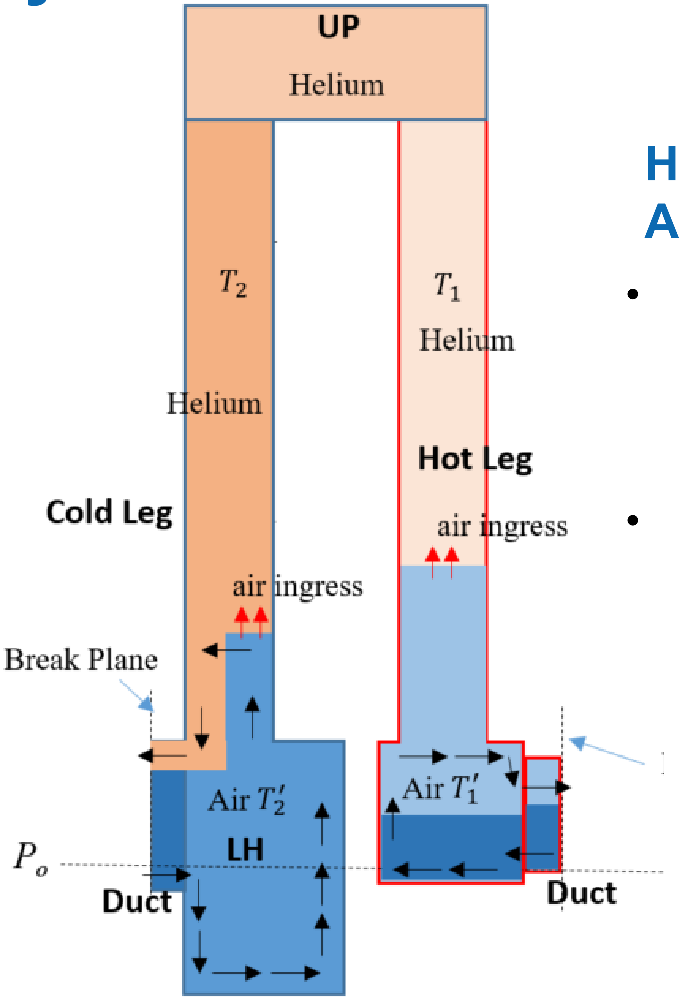
In addition to using the accelerator to generate radiation damage, exposure can be performed in high temperature mixed-gas reactors

High Temperature Gas Reactor Safety

Passive Safety Thermal Radiation



- Certain small HTGR concepts decay heat removal driven by:
  - Thermal radiation and conduction mechanisms within the reactor vessel or containment
  - Natural circulation outside the reactor vessel.
- Apparatus measures:
  - Emissivity at high temperature conditions in the range of 1400 to 1600°C
  - Non-metallic samples
  - Setting up to commission apparatus with graphite specimens.



HTGR Air Ingress

- Design of scaled experimental apparatus to study air ingress in HTGRs
- Onset of natural circulation of air through the core region in a postulated HTGR primary circuit break

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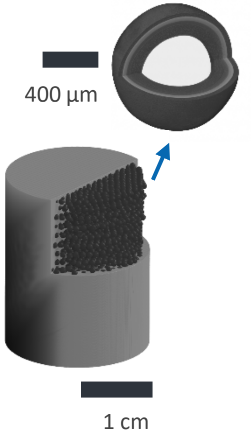
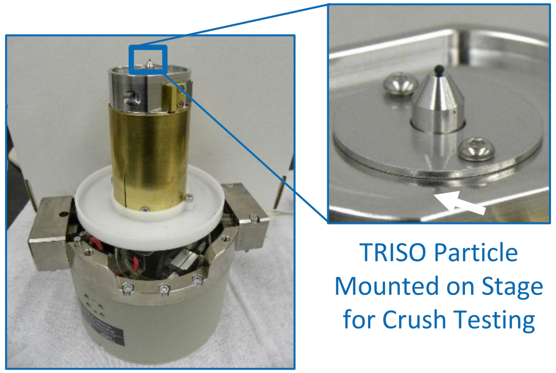
TRISO Fuel Research





TRISO Particle Mounted on Stage for Crush Testing

In-Situ Compression Stage for XCT

X-ray Computed Tomography (XCT)

- XCT has non-destructively imaged as-fabricated surrogate TRISO particles and compacts, elucidated the different buffer, IPyC, SiC, and OPyC layers
- Elevated temp XCT in-situ compression stage to determine the failure strength and particle failure behavior

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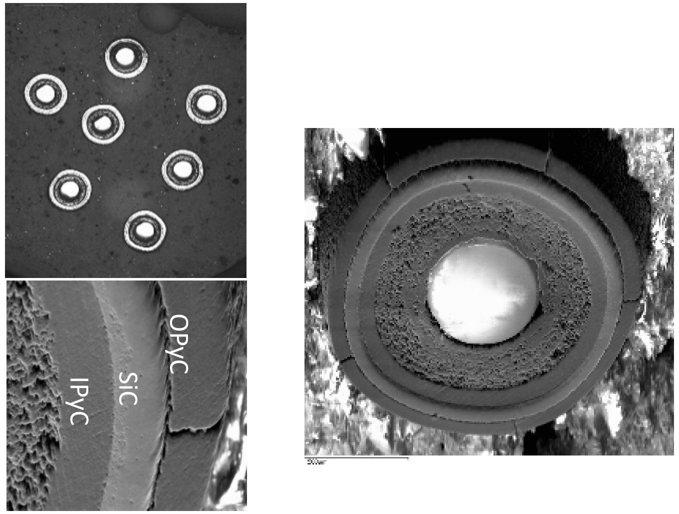


Microscopy and Nano-indentation

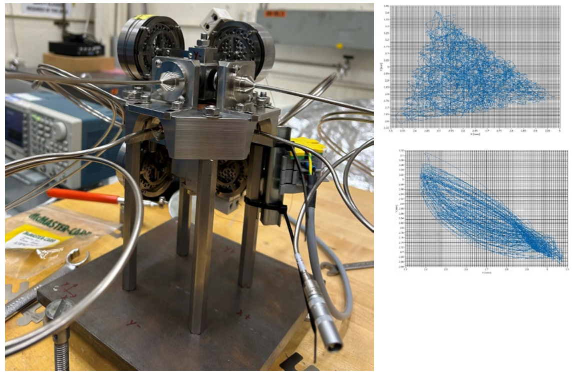
- Microstructure examination to determine high-temp mechanical properties of SiC layer and interface characteristics
- Hardness & elastic modulus property testing is ongoing at room temp. and up to 500°C by nano-indentation

Surrogate TRISO particle

Specimen Assembly in Graphite Irradiation Rig

High-Energy Proton Irradiations

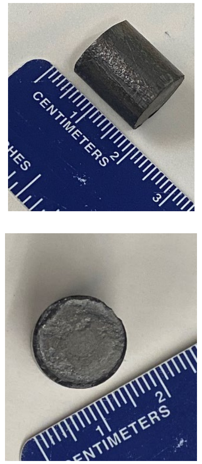
- Investigation of high-temp proton irradiation at TRIUMF on the integrity of surrogate TRISO fuel, specifically SiC layer behaviour



Development of Fretting-Wear Testing

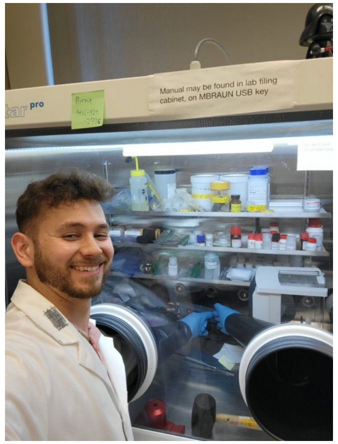
- Impact fretting wear testing in a Helium environment at 700°C
- Study effects of interface geometry, material pairing, process conditions, and vibration conditions

Fabrication



- Spark Plasma Sintering to fabricate compacts containing surrogate TRISO particles
- Preliminary effort to sinter graphitic matrix material has produced compacts above 80% of the theoretical density of graphite
- Pellet imaged had a density of 1.766 g/cm^3
- Characterization with XCT and SEM-EDS underway

TRISO Fission Product and Fuel Performance



Oak Ridge National Laboratory

UTSA The University of Texas at San Antonio™

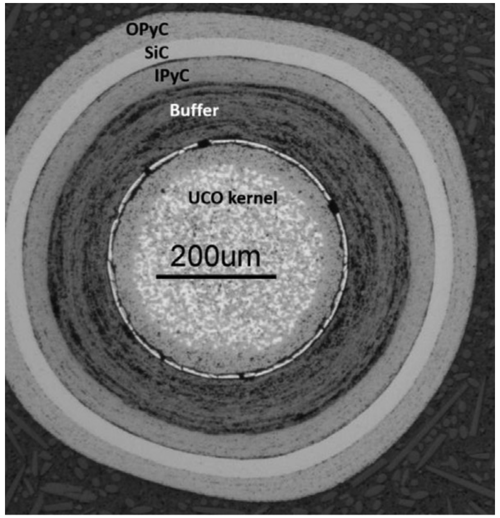
OntarioTech University

Before

After

Fission Product Solubility Experiments

R. Varga, MASc Thesis, Ontario Tech, Oshawa, Canada, in-preparation.



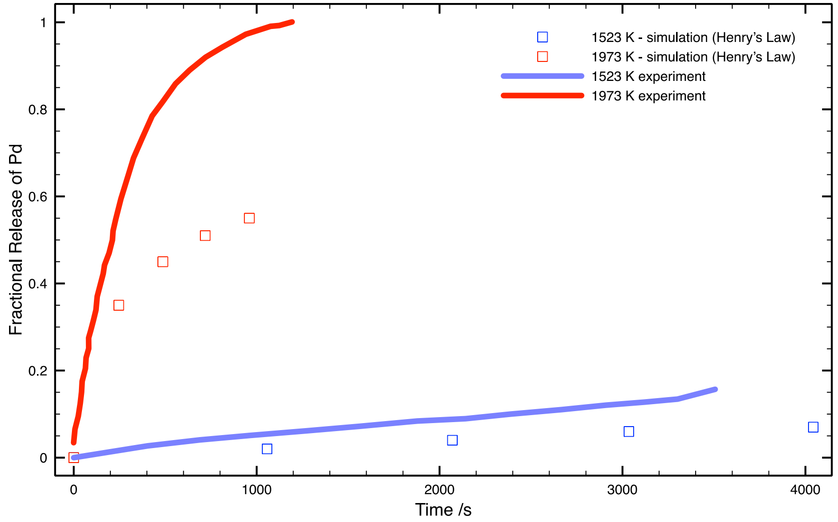
Oak Ridge National Laboratory

University of South Carolina

OntarioTech University

Funded by a subcontract with ORNL.

P.A. Demkowicz et al. / Journal of Nuclear Materials 515 (2019) 434-450



B.W.N. Fitzpatrick, M. Poschmann, T.M. Besmann, S. Simunovic, M.H.A. Piro, CANDU Fuel Conference (2022).

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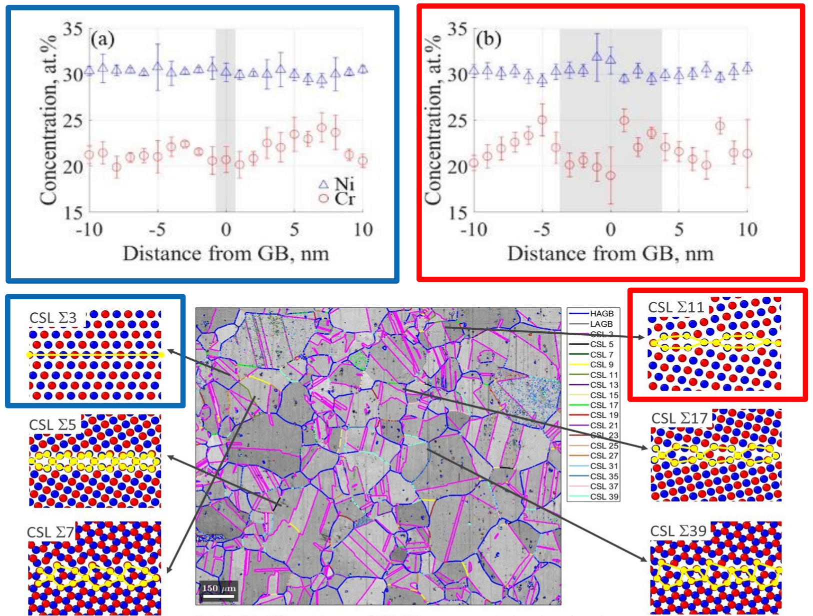
Modelling

Materials Modelling

Molecular Dynamics (MD) modelling to reproduce various grain boundaries (GBs) from experiments.

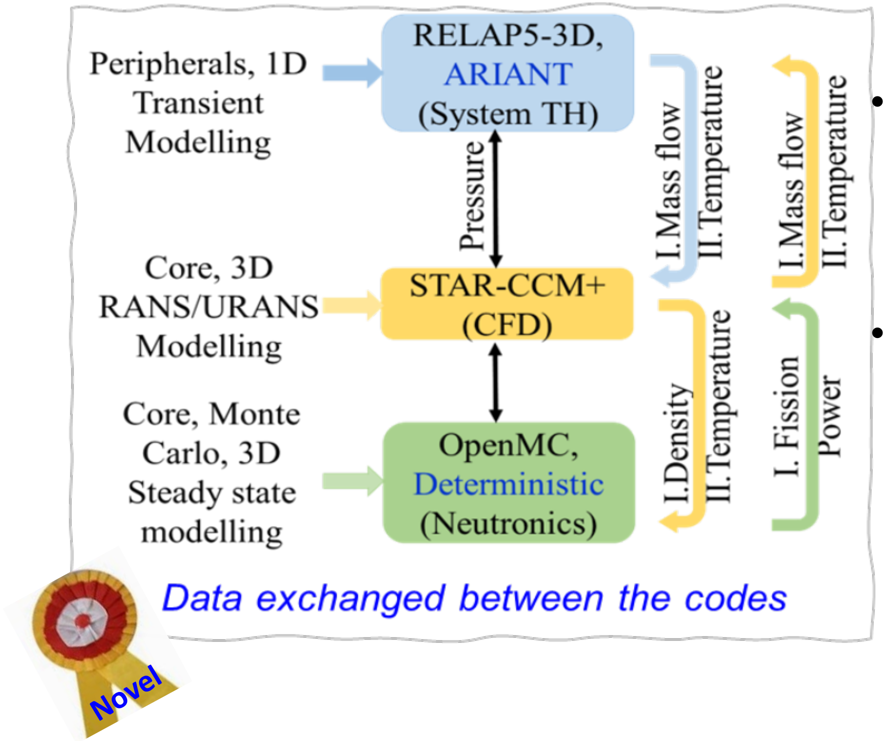
Elements segregation at grain boundary



Totally 18 different types of CSL GBs were created and analyzed.
GB energy is an important factor on radiation-induced segregation.

Neutronics/Thermalhydraulics

- Coupled codes
- ARIANT/RELAP5-3D/CFD/OpenMC



Peripherals, 1D Transient Modelling

RELAP5-3D, ARIANT (System TH)

Pressure

Core, 3D RANS/URANS Modelling

STAR-CCM+ (CFD)

Core, Monte Carlo, 3D Steady state modelling

OpenMC, Deterministic (Neutronics)

I. Mass flow
II. Temperature

I. Mass flow
II. Temperature

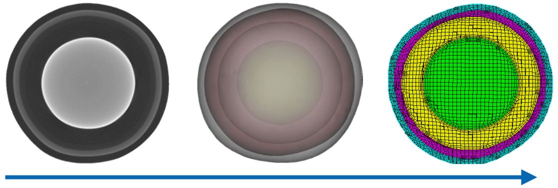
I. Density
II. Temperature

I. Fission Power

Data exchanged between the codes

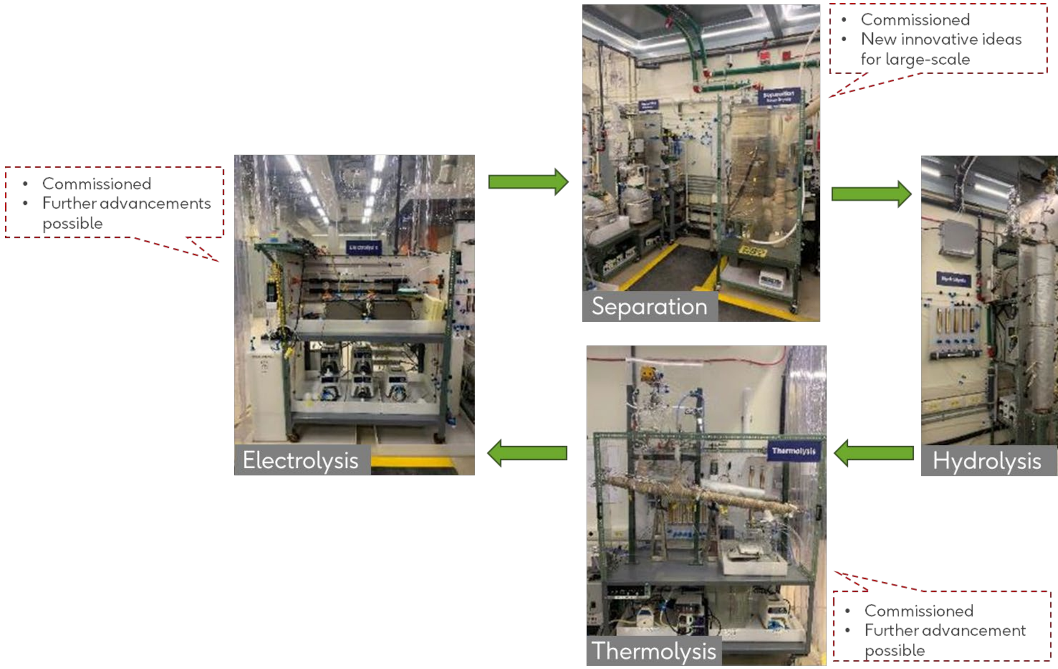
Fuel Modelling

- Impact of fabrication parameters and on QC requirements
- TRISO layers segmented from XCT scans can have FEM mesh applied using CUBIT/Sculpt
- BISON used to simulate irradiation performance with geometric imperfections, refining physical representation
- Simulation of the development of stress and the nucleation/propagation of cracks in surrogate TRISO under thermo-mechanical loads



Analysis Pipeline

Hydrogen Technologies



- Commissioned
- New innovative ideas for large-scale

- Commissioned
- Further advancement for scale-up

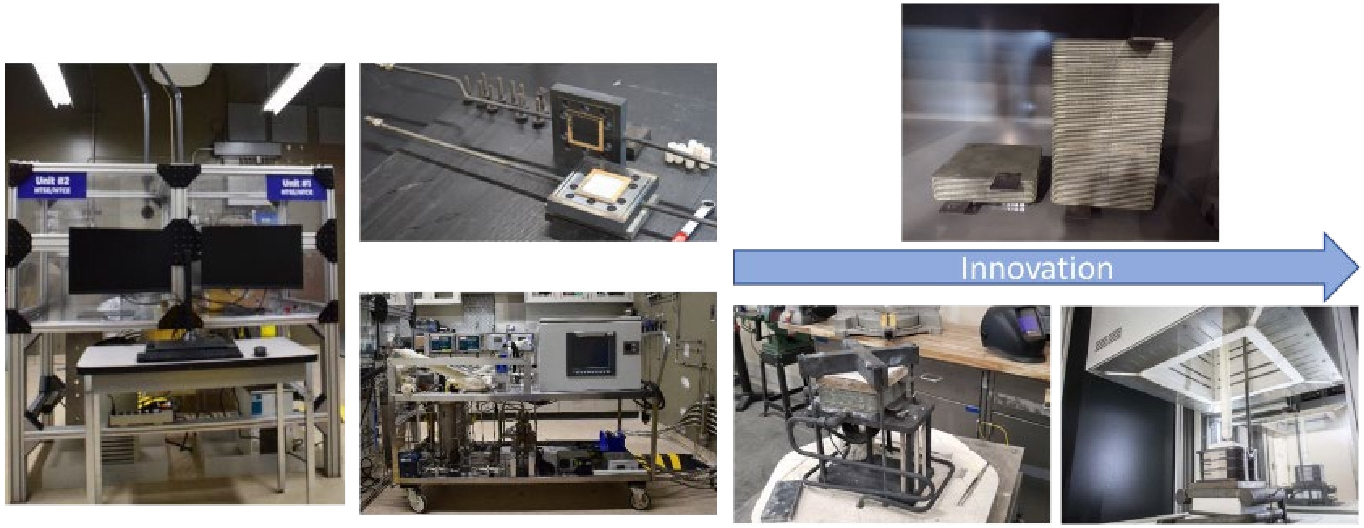
- Commissioned
- Further advancement possible

- Commissioned
- Further advancements possible

Demonstration of Cu-Cl Cycle at Minimum 100 g H_2/d (50 L/h) with Lab Equipment

High Temperature Steam & CO_2 Electrolysis

- Single cell & 3.5 kW multi-stack cell in High Temperature Steam
- CO_2 co-electrolysis development for H_2 & Syngas production



Single-cell developments

Multi-cell testing

Sodium Fast Reactor Research Summary

Corrosion

Experimental corrosion studies for long term storage of used fuel

Fuel Processing

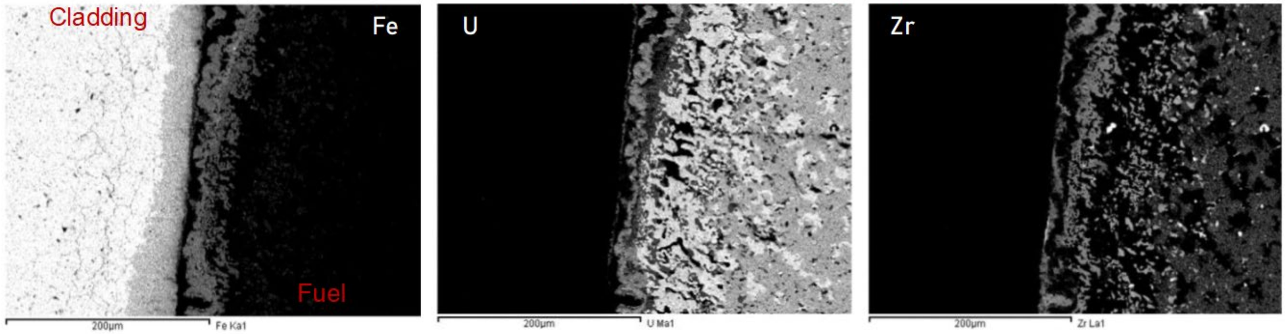
- Sodium handling
- Fuel fabrication
- NDE

Computational Modelling

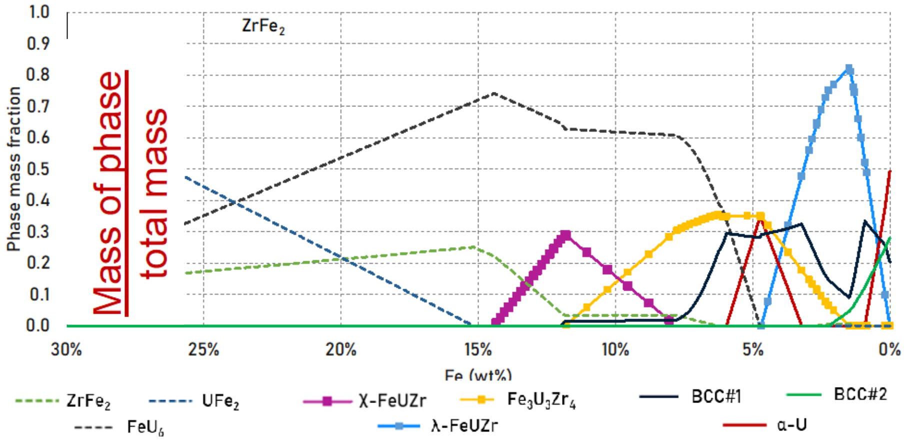
- Fuel performance
- Fuel – clad chemical interaction
- Spent fuel management/ depletion calculations

SFR Fuel Cladding

Elements X-ray maps, from JNM 494 (2017) 227

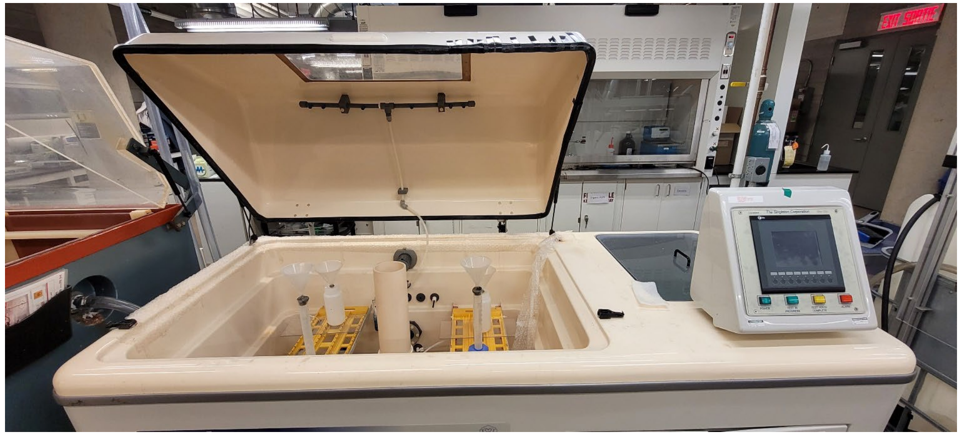


Fuel Clad Chemical Interaction



Mass fraction of cladding into the fuel

E. Geiger, C. Gueneau, E.C. Corcoran, M.H.A. Piro, J. Nucl. Mater., 551 (2021) 152981.



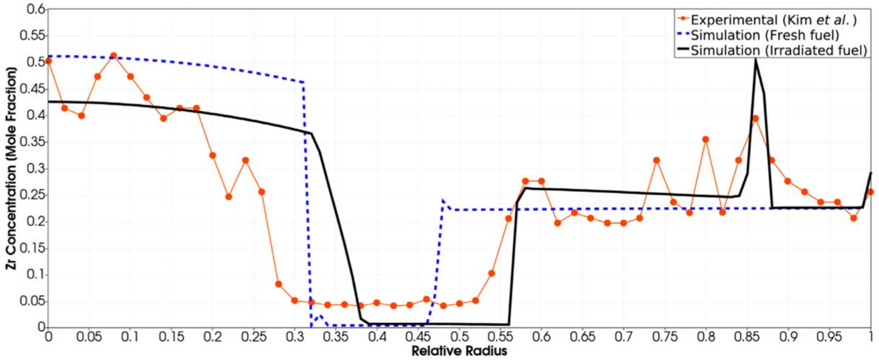
Chemistry Control During Long-Term Storage of SMR Used Fuel

- Sodium bond between metallic fuel and fuel cladding material can react if exposed to water during DGR flooding
- Fabricate cladding final waste form via additive manufacturing methods
- Custom leak test cell to be designed and commissioned onsite at CMAT to quantify reaction products and their effects on fuel cladding when water interacts with sodium

SFR Fuel Research Activities

CNL - Metallic Fuel Processing

- Safety aspects of handling sodium
  - During fuel fabrication process
  - Disposition of spent fuel
- Sustainability of metallic fuel fabrication process
- Non-destructive techniques for fuel inspection



Metallic Fuel Performance Simulations

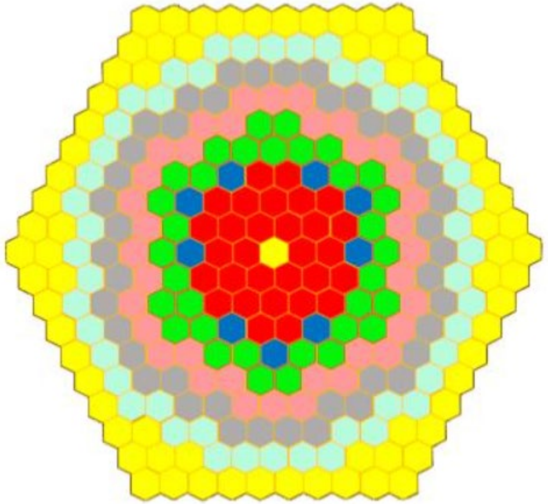
- BISON + Thermochimica simulations of UPuZr metallic fuel
- Zr diffusion driven by chemical potential gradients, thereby incorporating the effects of irradiation on solid state diffusion

OAK RIDGE National Laboratory

UNIVERSITY OF South Carolina

TEXAS The University of Texas at Austin

OntarioTech UNIVERSITY



Spent Fuel Characteristics

- Serpent 3D core physics mode
- Spent fuel management
- Depletion calculations

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Heat Pipe Research Summary

Experimental Testing

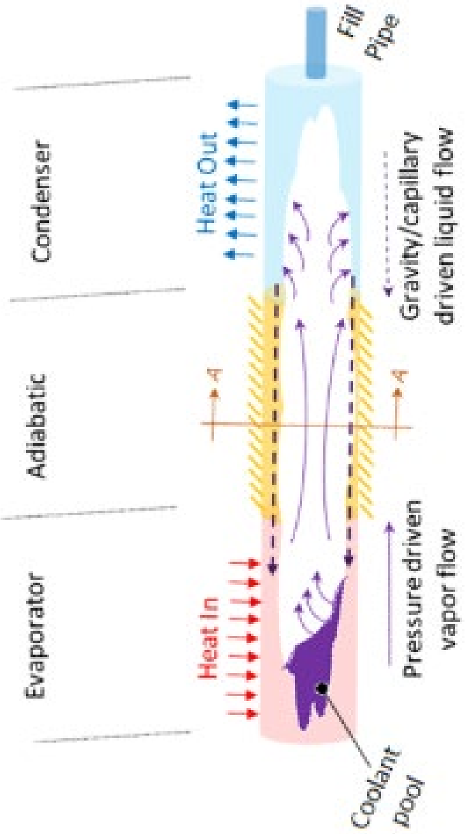
- Sodium and potassium heat pipe apparatus
- Single and array sodium heat pipe

Computational Modelling

- Thermophysical properties of saturated sodium and potassium
- Simulation of sodium single heat pipe experiments

Heat Pipe Research

Sodium and Potassium Heat Pipe Apparatuses



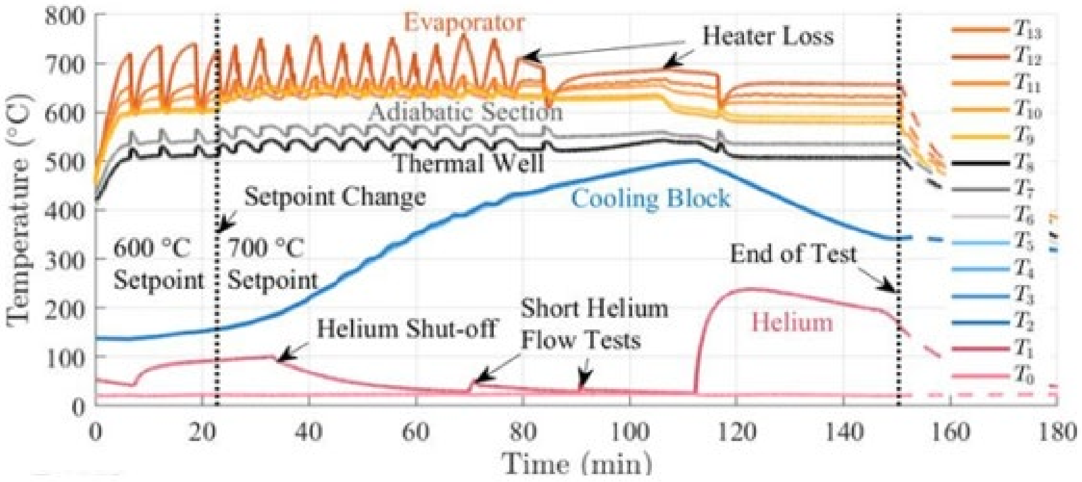
- **Sodium heat pipe (single)**
  - Tested up to 750°C
  - Steady-state tests
  - Cyclical tests, start-up, shutdown
- **Sodium heat pipe (array)**
  - Tested up to 650°C
  - Rupture of one or multiple heat pipes
- **Potassium heat pipe (single)**
  - Test up to 650°C
  - Steady-state tests
  - Start-up and shutdown

Assembled and instrumented array **sodium heat pipe**

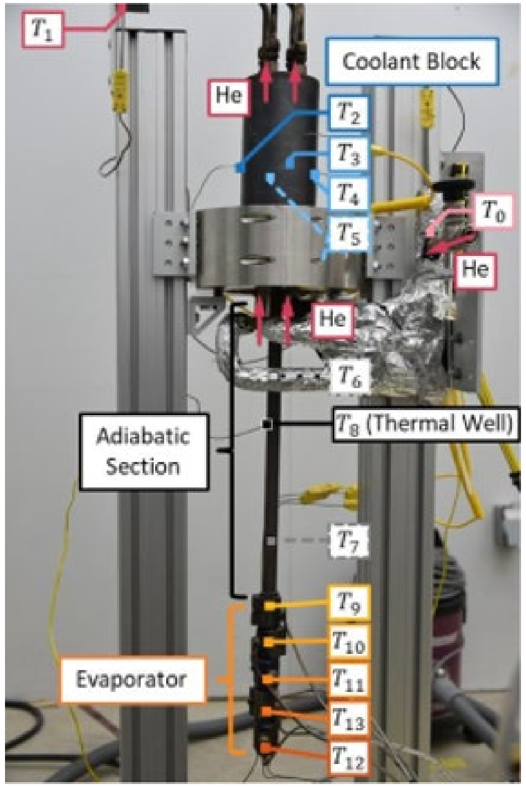
Heat Pipe Research

Experimental Results from Single Heat Pipe

- Transient behaviour of heat pipe
- Achieving test conditions and providing data for:
    - Model/code development
    - Understanding phenomena
    - Model/code benchmarking



Computational Modelling of Heat Pipes



- ARIANT heat pipe module
    - Thermophysical properties of saturated sodium and potassium
    - Simulation of sodium single heat pipe experiments.
- STAR-CCM+
    - Solid, liquid, gas transitions

Canadian Nuclear Laboratories

Laboratoires Nucléaires Canadiens

Summary

SMR Development in Canada

- Advanced Water-Cooled Reactors
- Sodium Fast Reactors
- Molten Salt Reactors
- Very/High-Temperature Gas-Cooled Reactors
- Microreactors

R&D Focus Areas

- Materials & chemistry
- Advanced fuel development
- Advanced material development
- Neutronics
- Thermalhydraulics
- Safety & accident analysis
- Computational modelling
- Security & safeguards
- Hydrogen technologies

Facilities, Funding & Collaborations

- Labs
- Research Institutes
- Universities

Supported by programs:

- FNST
- NRCan
- NRCan-NSERC
- NRCan-CNSC

Collaborations:

- GIF
- IAEA
- NEA Working Groups
- EU Horizon
- USDOE

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Thank you!

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Upcoming Webinars

Date	Title	Presenter
17 April 2024	Multiphysics Depletion & Chemical Analyses of Molten Salt Reactors	Sam Walker, INL, USA
22 May 2024	Joint GIF/IAEA Webinar: Regulatory Activities in support of SMRs and Advanced Reactor Systems	Paula Calle Vives, IAEA Tarek Tabikh, CNSC, Canada Greg Oberson, NRC, USA
05 June 2024	Directed Energy Deposition Process of Corrosion Resistant Coating for Lead-Bismuth Eutectic Environment	Gidong Kim, UNIST, Korea