Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Establishing a Framework for Advanced Manufacturing of Molten Salt Reactor Components Using Powder Bed Fusion and Direct Energy Deposition

NRCan – Enabling Small Modular Reactors Program

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Agenda

- Background
- What Makes This Disruptive?
- Project Structure
- Year 1 Progress
- Year 2 Plan
- Year 3 Plan & Project Deliverables
- Upcoming Activities
- Discussion / Questions

Background

- In 2023, NRCan introduced the Enabling Small Reactors Program with the objective to support the development of supply chains for SMR manufacturing and SMR fuel supply.
- In 2024, CNL, in collaboration with InnoTech Alberta, received funding under the program for "Guidelines for Implementing Advanced Manufacturing Technologies in the Canadian Nuclear Industry".
- Enabling Small Modular Reactors Program: Funded projects - Natural Resources Canada

What makes this disruptive?

- SMRs present an opportunity to modernize the nuclear supply chain and aim to limit high upfront costs of reactor construction and the inherent risks of large nuclear installation projects.
- Advanced manufacturing techniques may play a key role in helping achieve these objectives by:
  - Lowering upfront capital investments
  - Simplifying complex assemblies of many parts
  - Addressing low production volumes
  - Raising interests from new manufacturers to enter the nuclear supply chain
- <u>Application</u> of a unique set of codes, standards, and regulations remain a challenge.

What makes this disruptive?

- Brings together SMR vendors / designers, advanced manufacturing suppliers, and regulatory bodies.
- Navigates the engineering, quality, and regulatory challenges.
    - Fabricate a scaled version of a SMR component using advanced manufacturing techniques (laser powder bed fusion and direct energy deposition).
    - Perform inspections and tests to evaluate properties of 3D printed components and coupons.
- Communicate how a vendor could supply advanced manufacturing services in support of new and novel advanced reactor designs.

Project Structure

Year 1: Selection of component

- SMR vendor and supplier survey
  - Select demonstration component and material
- Define manufacturing steps, heat treatments, inspections, and testing steps

Year 2: Component and test coupons manufacturing and testing

- Produce components and test coupons (LPBF and DED)
- Perform coupon and component analysis and testing

Year 3: Preparation of deliverables

- Test reports
- Guidelines document

Year 1 Progress

- A recent survey of (600+) stakeholders in the nuclear sector identified that:

Topic	Response
3D printing will play a **significant role** in the future of SMR design and manufacturing	**Yes (53%)** No (12%) Not sure (35%)
Benefits in using 3D-printed components	**Cost reduction (26%)** **Reduced lead time (26%)** Customization of parts (22%) Other (enhanced performance, new materials) (26%)
Foreseen **challenges** on the use of 3D printing for SMR components	**Regulatory approval and compliance (53%)** Other (lack of approved vendors, QC, QA, scalability) (47%)
Improvements recommended for 3D-printed components in SMRs	**Regulatory and certification process (47%)** Material performance (24%) Other (post-processing methods, part design) (29%)

Year 1 Progress (continued)

- The survey also highlighted areas of interest for 3D printing:

Reactor Type	Components	Materials	Size
Molten-salt reactor	**Heat exchanger**	**Stainless steels**	**30 cm x 30 cm x 30 cm (or smaller)**
	Structural components	**High-temperature alloys (Inconel, Hastelloy)**	30 cm x 30 cm x 30 cm (or larger)
Boiling Water Reactor	Cooling system parts	Zirconium alloys	
Sodium Cooled Fast Reactor	Fueling system parts	Titanium alloys	

Year 1 Progress (continued)

- Laser Powder Bed Fusion (LBPF):
  - Uses a high-powered laser to melt and fuse metal powder particles layer by layer for precise part creation.
  - Good for highly complex geometries.
  - Process Steps:

Source: Stratasys

Powder Layer Application
- Powder is spread using recoater blade

Laser Melting and Fusion
- Laser selectively melts and fuses powder

Layer Building
- Build platform lowers, allowing the next layer to be built

Post Processing
- Heat treatment
- Solution annealing
- Surface finishing

Year 1 Progress (continued)

- Component selected for LPBF:
  - TPMS Gyroid Heat Exchanger:
    - Optimized for heat transfer and fluid mixing
    - High surface area-to-volume ratio
    - Smooth, continuous geometry minimizes stress concentrations
    - Functional dimensions: 35 cm x 35 cm x 35 cm
  - Material: Inconel Alloy 625 (Ni-Cr-Mo)
    - Superior corrosion resistance, high strength, and heat resistance across a wide temperature range

Source: nTopology

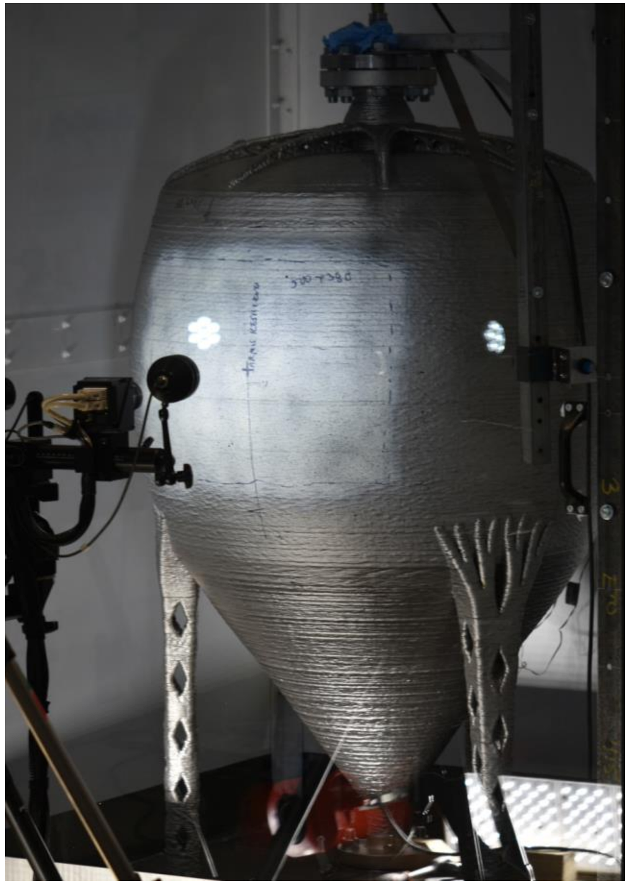
Year 1 Progress (continued)

- Directed Energy Deposition (DED) – WAAM:
  - Uses a metal wire as feedstock and an electric arc as the energy source to build parts layer by layer.
  - Ideal for large-scale components.
  - Process Steps:

Wire Feeding
- Metal wire is continuously fed into the deposition zone

Arc Generation
- An electric arc melts the wire and a portion of substrate
- Molten metal is deposited in a bead (similar to welding)

Post-Processing
- Solution annealing
- Machining
- Surface treatment



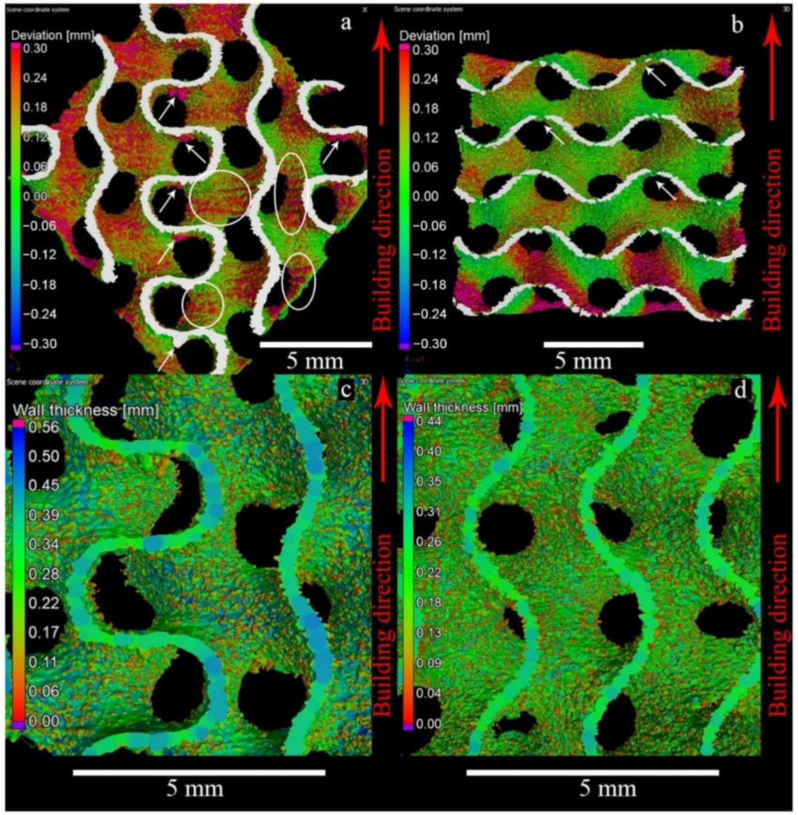
Source: FAME Ecosystem

Year 1 Progress (continued)

- Component selected for DED:
  - Transition duct:
    - Compact design: smooth and gradual transition of flows
    - Functional dimensions: 1 m x 1 m x 2 m
    - Scaled dimensions: 0.25 m x 0.25 m x 0.50 m
  - Material: Inconel Alloy 625 (Ni-Cr-Mo)
    - Superior corrosion resistance, high strength, and heat resistance across a wide temperature range

Year 1 Progress (continued)

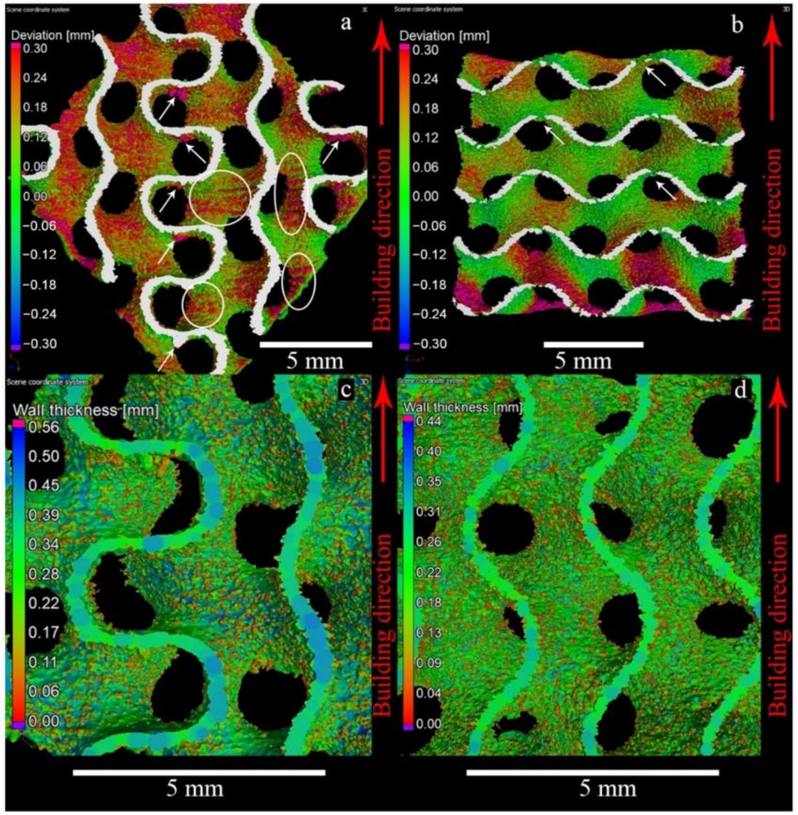
- Manufacturing, Inspection, and Test Plan (MITP) Preparation:
  - Purpose: Specify the steps, inspections, tests, and acceptance criteria
  - Modelled after ASME BPVC Section III Div 5 Framework
    - Elevated temperature nuclear components
  - Inclusive of:
    - Metallographic examinations
    - Standard material tests
    - Aging material tests
    - Dimensional inspections



Source: DOI:10.3390/ma14174912

Year 2 Plan

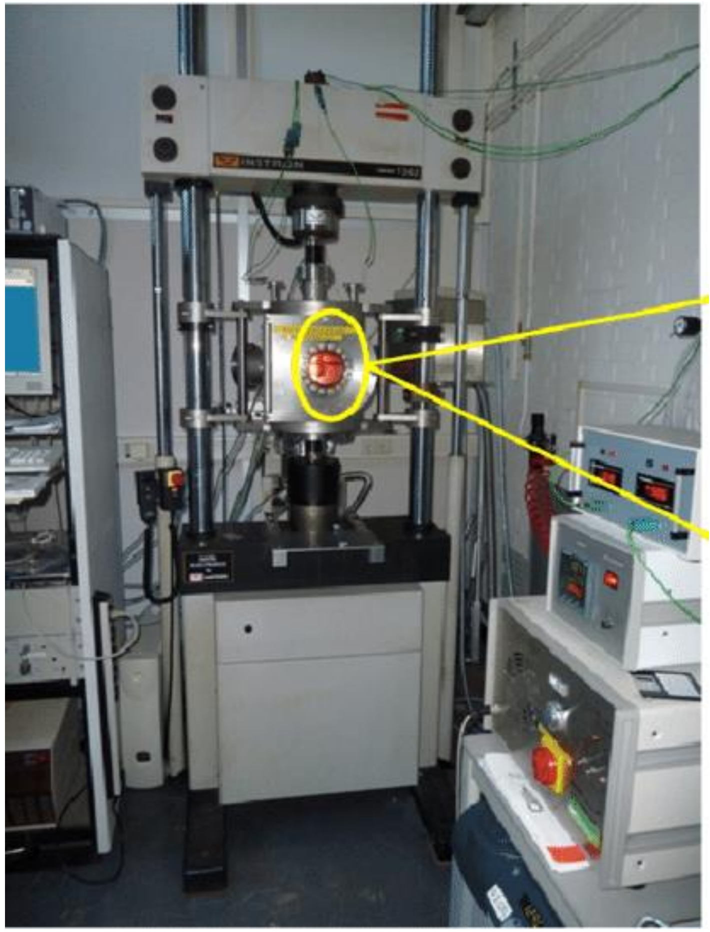
- Metallographic examinations:
  - Microstructure
    - Grain size
    - Phase distribution
    - Anisotropy
  - Porosity
    - Identify voids/gas entrapment
    - Investigate lack of fusion



Source: DOI:10.3390/ma14174912

Year 2 Plan (continued)

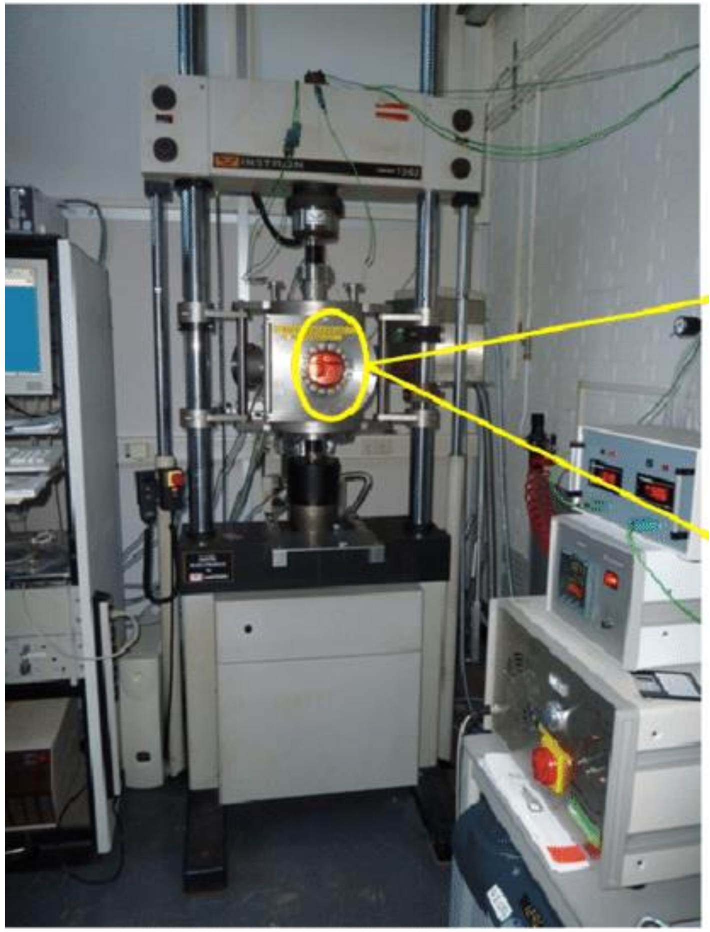
- Standard material tests:
  - Tensile testing (before/after ageing)
    - Evaluates strength and ductility.
    - Detects anisotropy from build orientation and thermal gradients.
  - Hardness testing
    - Sensitive to microstructural variations and porosity.
  - Impact testing (before/after ageing)
    - Measures toughness and resistance to sudden loads.
    - Important for safety-critical applications and post-processing validation.



Source: High Temperature Materials Testing for Fusion Applications at NRG

Year 2 Plan (continued)

- Additional material tests:
  - Fatigue Testing
    - Evaluates strength and ductility under cyclic loading.
    - Useful for assessing long-term performance and identifying potential failure modes
  - Fatigue-Creep Testing
    - Combines cyclic and sustained loading to simulate real-world service conditions.
  - Fracture Toughness Testing (before/after ageing)
    - Measures a material's resistance to unstable crack extension under load.



Source: High Temperature Materials Testing for Fusion Applications at NRG

Year 2 Plan (continued)

- Dimensional inspections:
  - 3D scanning
    - Captures external geometry with high resolution.
    - Verifies part accuracy against CAD models.
    - Useful for detecting warping or build deviations.
  - Coordinate Measuring (CMM)
    - Verification of tolerances on machined or post-processed AM parts.
    - Complements 3D scanning and CT for full geometric validation.
  - X-ray CT scanning
    - Provides internal and external dimensional data, including internal HE channels.
    - Detects hidden defects like porosity, cracks, and inclusions.

Year 3 Plan & Project Deliverables

- Deliverables:
  - Test reports
    - Microstructure and porosity examinations
    - Tension, hardness, fatigue, fatigue-creep, and impact testing
    - Component-scale testing
  - Guidelines document
    - Steps on implementing advanced manufacturing techniques
    - Share lessons learned from the case studies
    - Structured as a CSA standard

Upcoming Activities

- Partnership:
  - Finalize partnership with SMR vendor / designer
- Design:
  - Complete designs for 3D printing of gyroid heat exchanger and transition duct
- Printing:
  - Perform LPBF and WAAM printing trials

References

- **Images:**

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Discussion / Questions