ADVANCED MANUFACTURING ROADMAP FOR THE CANADIAN NUCLEAR INDUSTRY

A Potential Solution to Address CANDU Obsolescence Challenges and to Reduce Fabrication Costs of SMR Components

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A. Purpose and Scope

The purpose of this Advanced Manufacturing Roadmap is to demonstrate why advanced manufacturing is important for sustaining the Canadian CANDU fleet until 2065 and beyond and for enabling Canada to be an SMR leader. The roadmap lays out a high-level plan on how to develop advanced manufacturing capacity in the nuclear supply chain and highlights some of the ongoing projects in the nuclear advanced manufacturing space.

This draft roadmap will focus on additive manufacturing (AM) as a starting point that will allow for specific (rather than generalized) discussion. Other advanced manufacturing technologies can/will be included in the Advanced Manufacturing Roadmap through the engagement of other industry and academic partners in charting the path to bring advanced manufacturing to the nuclear industry noting the widespread use in the aerospace sector for example.

The Organization of Canadian Nuclear Industries (OCNI) and its member company KSB bring important perspectives to this roadmap. OCNI has a mandate to support and strengthen the Canadian nuclear supply chain by assisting member companies in enhancing their capabilities and implementing new technologies. KSB has become a world leader in implementing additive manufacturing methods in the manufacturing of pumps and valves and related replacement (obsolete) components for the power sector. KSB has also developed additive manufacturing expertise in a broad range of parts and equipment, beyond pumps and valves, using numerous metal alloys.

This roadmap was also developed with support from Kinectrics and Burloak who have entered into a partnership to design, manufacture and qualify additively manufactured parts for nuclear facilities in Canada and worldwide. Kinectrics provides life cycle management services for the nuclear industry as well as the electricity transmission and distribution industry. Kinectrics has the capabilities to perform equipment qualification for reactors within Canada and internationally. Burloak is a Canadian company at the forefront of additive manufacturing supplying components to the aerospace, automotive and medical industries. Burloak's facilities include technology such as electron beam powder bed fusion, laser–powder bed fusion, high-speed extrusion, fused deposition modelling, directed energy deposition, selective laser sintering and binder jetting and is capable of printing over 20 different metals and polymers.

B. Background, Context, Assumptions

Additive manufacturing is an advanced manufacturing technique incorporating three main components. First, there needs to be a computer-aided design (CAD) model which is "sliced" into horizontal layers which can be read by computer software. The second aspect of AM is a material, metals, plastics and even ceramics can be printed using various techniques by feeding raw materials into the machine. Metals are often loaded in powder form, other materials such as plastics can come in rolls which are fed through a nozzle, as a granulate or as a powder. The final aspect of additive manufacturing is a heat source that is used to join the raw material through melting, sintering or other adhesion methods. While there are many different types of additive manufacturing such as laser-powder bed fusion, selective laser sintering, binder jetting, directed energy deposition and high-speed extrusion, the main three components are common between all. AM machines work to manufacture each component vertically layer by layer adding material with layer heights on the order of microns.

As Canadian nuclear plants continue to age, there is an increasing need to replace many of the ageing or broken components within these plants. Many of these reactors were built with parts supplied by companies who have ceased production sometime between now and initial construction, or no longer produce the same part that was originally supplied. The current solution to these problems requires an expensive engineering and procuring process to find a part of similar function while not compromising the efficiency or safety of the plant. Many utility companies try to avoid these issues by constructing and staffing large warehouses and stockpiling plant components for future use adding to the expense of part replacement, but even in this scenario the parts can deteriorate over time if conditions are not kept within storage specifications.

Reverse engineering and digitization of obsolete components in ageing nuclear plants can enable these components to be directly “printed” quickly and cost-effectively or produced by conventional means using moulds “printed” from the digitized design. A diverse AM supplier base can also provide the ability to complete in-situ repairs and coatings which could be very beneficial to nuclear power plants (NPPs). A Canadian CANDU supplier base with this AM capability will be essential in sustaining the Canadian CANDU fleet to 2065 and beyond.

Advanced manufacturing can be used to make complex and intricate SMR components that were heretofore beyond the reach of conventional manufacturing or make larger components faster and cheaper than by conventional methods. These AM features combine to promise cost and schedule reductions and enable optimized design features that will help make SMRs cost-competitive with other forms of energy production. Investing in AM as outlined in this roadmap will help make Canada a leader in both domestic and international SMR deployments. However, additive manufacturing requires much more than hitting the print button. High-quality, repeatable production requires a broad range of interlinked capabilities and equipment. Printing is only one element of the additive manufacturing process as demonstrated in Exhibit A below.

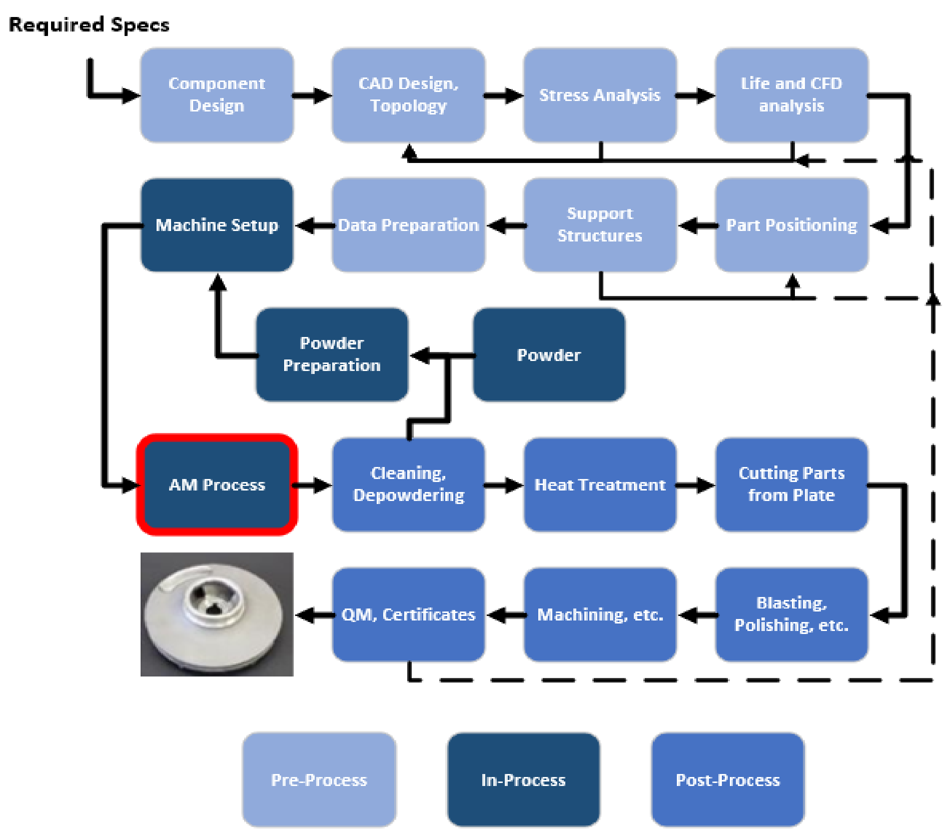

Exhibit A: Additive Manufacturing Flowsheet and Quality Process

It is recognized that additive manufacturing technologies will continue to evolve significantly over the coming decades. Additive manufacturing is already established as a commercially viable manufacturing approach for the fabrication of critical components in operation in high-performance applications such as a jet engine fuel nozzle (20 parts reduced to one) and jet engine turbine blades see [1], [2].

It is therefore imperative that the nuclear industry should develop a plan now for implementing additive manufacturing and other advanced manufacturing methods in order to leverage the advantages advanced manufacturing can provide and to be positioned to capture increased benefits as AM technology continues to evolve and improve. AM equipment and processes will continually evolve to be capable of:

- producing larger parts
- embracing more modalities
- utilizing more alloys and materials
- readily producing consistent (predictable) quality of finished parts
- reducing production costs through reductions in capital costs of AM equipment & operating costs

It is anticipated that more AM suppliers will enter the market over time and will offer more competitive pricing and better service capabilities.

As AM is adopted into the nuclear industry it is imperative that standards are reviewed and updated as required. A few organizations have already begun updating their standards for general additive manufacturing including ISO, ASTM and CSA. Each of these organizations has undergone a review of their current standards and has begun to produce new standards and update old ones to fill in the gaps introduced by additive manufacturing.

Some examples of these AM specific standards:

- ASTM F2971 - Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
- ASTM F2792 – Standard Terminology for Additive Manufacturing Technologies
- ASTM F3049 - Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes
- ASTM F3122 - Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes
- ASTM F3413 - Guide for Additive Manufacturing — Design — Directed Energy Deposition
- ISO/ASTM52902-19 - Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems
- ISO/ASTM52903-1-20 - Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 1: Feedstock materials
- ISO/ASTM52910-18 - Additive manufacturing — Design — Requirements, guidelines and recommendations

This list is not exhaustive and is only shown as an example of standards that have been produced for additive manufacturing.

Specifically in the Canadian nuclear space, the CSA conducted a review in 2019 where they developed a task force on advanced manufacturing. This task force reported that there are **no critical barriers stopping the adoption of additive manufacturing** but will continue to update their standards to provide additional guidance in areas they identified that could be improved (Appendix A). Industry-specific AM standards have been created for other industries such as aerospace and medical which will act as references for developing nuclear AM standards in the future.

AM training facilities will become available and general AM expertise will increase across the manufacturing sector. Exhibit B illustrates the expected continued cost reductions with the more widespread application of AM technology in the industry.

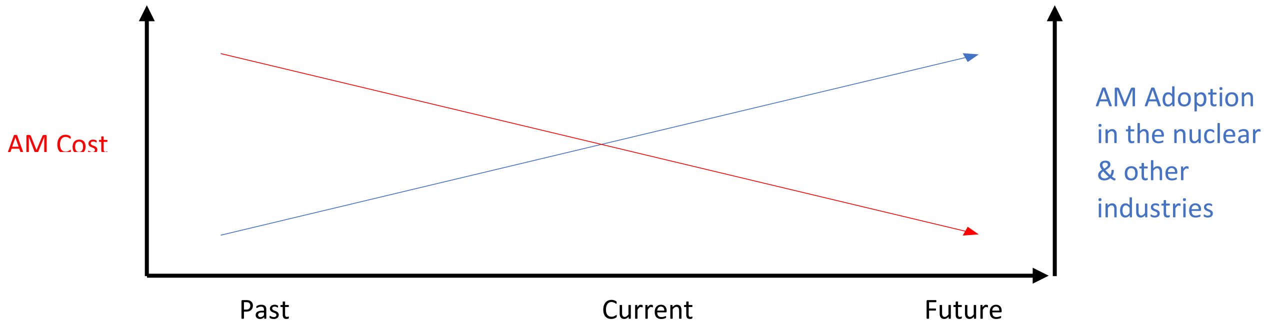

Exhibit B: Predicted AM Cost Reduction with Increased Adoption in Nuclear and Other Industries

C. Current Status of Market

Currently, additively manufactured parts are being used in a variety of industries including aerospace, automotive, medical and product development. Some examples of industries that use the advantages of AM regularly include:

Aerospace: AM provides increased complexity in part geometry and decreased weight and can even produce geometries that were physically impossible using traditional subtractive methods. This allows aircrafts and rockets to save weight which in turn burns less fuel making flights cost significantly less while maintaining the same level of safety. The aerospace industry also uses AM to reduce complex assemblies into single parts due to its advanced geometries with examples of up to 20 parts being combined into a single part which can reduce failure points, assembly costs and lead times.

Medical: The medical industry utilizes AM parts for implant applications such as hip and knee replacements. AM allows for custom-made parts that can be quickly manufactured and can reduce the number of parts needed per implant.

Automotive: Much like the aerospace industry, the automotive industry uses AM technology to print parts with less weight and smaller footprints. This allows for greater fuel efficiencies while keeping production costs low and remaining safe. The automotive industry also uses AM parts to address obsolescence such as supplying parts for older vehicles whose original part supplier has gone out of business or stopped manufacturing specific components.

Product Development: The product development industry has become a large adopter of AM technology taking advantage of the speed and cost benefits of the technology. AM is especially useful in prototyping parts as many designers use low-cost 3D printing machines to print plastic 3D models allowing for rapid prototype iterations while costing very little for the materials.

At the moment the international nuclear industry's adoption of AM technology consists of control room parts such as control knobs and electrical casings, some quality level 4 or equivalent components and a few pilot cases within reactor environments. The few pilot cases that have been completed for NPPs include a impeller completed in France by KSB, a fuel channel fastener completed in the US by Framatome and a thimble plugging device completed in the US by Westinghouse. U-Battery and Cavendish have also created a mock-up of a pressure vessel of an advanced modular reactor created using AM methods in the UK.

Internationally the UK and Germany are two leading examples of jurisdictions that are actively developing nuclear applications for advanced manufacturing. The United Kingdom has opened a research centre for advanced manufacturing in nuclear applications seen in Exhibit C. KSB has also opened up their own facility for additive manufacturing in Germany seen in Exhibit D.

Exhibit C: United Kingdom Nuclear Advanced Manufacturing Research Centre

Exhibit D: KSB Additive Manufacturing Center

Canadian University-Based Centres

Canadian-based academia has also begun to explore advanced manufacturing through the development of advanced manufacturing facilities expanding current research capabilities. Collaboration between the nuclear industry and academia will be essential to advancing additive manufacturing in the nuclear industry. Some examples of these facilities include:

- University of Waterloo’s Multi-Scale Additive Manufacturing Lab (MSAM)
- Toronto Institute of Advanced Manufacturing (TIAM)
- Research Council of Canada's (NRC) Advanced Manufacturing program and Canadian Campus for Advanced Materials Manufacturing (CCAMM)
- Concordia University’s Centre for Advanced Manufacturing
- Niagara College’s Walker Advanced Manufacturing Innovation Centre
- McMaster Manufacturing Research Institute (MMRI)

Many other institutions are conducting research on advanced manufacturing topics and the development of advanced manufacturing facilities is expected to grow in the coming years. One action of this roadmap is to obtain partners, funding and a location for a **Canadian Nuclear AM Training and Test Center** which were serve as an innovation hub supporting AM in the Canadian nuclear industry.

D. Potential Benefits for the Canadian Nuclear Industry

There are many areas in which additively manufactured parts can provide a benefit over traditional manufacturing methods within Canada including:

a. Obsolescence

The first benefit of additively manufactured parts in the Canadian nuclear industry will be the ability to manufacture parts that are currently obsolete at a reasonable price and time frame. Many companies who originally supplied Canadian plants have since ceased operation or no longer manufacture the same parts. When similar parts are not able to be procured, engineering changes must be completed which often consume considerable time and money.

Introducing AM as a viable manufacturing method for NPPs will be reliant on supplier reverse engineering programs using previous part drawings and 3D scanning techniques. These processes will allow suppliers to additively manufacture numerous parts that fall within the size and material limitations of the AM machines themselves and the material and quality standards set by various organizations.

b. Reduced Lead Times

AM manufacturing often has shorter lead times than traditional manufacturing due to a variety of factors such as fewer production steps, part consolidation and part optimization. The combination of manufacturing and post-processing time of AM-produced parts is often quicker than with traditional manufacturing methods. Also, depending on machine build volume and part size there are situations in which multiple parts can be printed within the same machine at one time improving the output of a supplier. Part optimization further decreases manufacturing time as AM parts often can be optimized for increases in strength and decreases in weight by only adding material where it is required, which speeds up the entire manufacturing process.

c. Higher Efficiency

Additively manufactured parts have the advantage of extremely complex geometries which are often hard to replicate, cost-prohibitive or even impossible with traditional manufacturing. These complex geometries can be leveraged to increase component characteristics such as heat transfer by incorporating complex fin shapes, cooling channels or heat exchangers with higher thermal capabilities and efficiency. There are also situations in which printing can remove the need for welding and fasteners creating fewer failure points and areas where leakage could occur.

d. Waste Reduction

Contrary to traditional manufacturing methods in which material is removed from a part, AM parts are manufactured by adding material. This allows AM parts to be much more efficient in the way that material is used and as a result have very little waste. AM processes can be as little as 3-5% waste whereas traditional manufacturing methods can see as high as 90% waste. This is a huge reduction especially when looking at exotic metals such as the allows often used in the nuclear industry.

e. Digital Part Warehouse

As AM increases its adoption in the nuclear industry and the full benefits of on-demand printing are realized there will be an opportunity to create a digital warehouse of parts further adding to the benefits of AM. This warehouse would consist of a virtual catalogue of CAD files of parts often required in nuclear applications and can be referenced by any supplier of nuclear parts allowing for suppliers to skip the reverse engineering aspect of 3D printing and immediately begin production.

Unlike the current warehouses where parts are stockpiled until they are needed, a digital warehouse cost very little to maintain. It also does not take up any space, does not allow the parts to deteriorate over time and is more secure reducing costs by hundreds of thousands to millions a year. There is also a possibility for utilities to reuse existing storage facilities to store raw AM materials such as metal powders which is more cost-effective than storing entire parts.

f. SMRs

Some SMR designers are already planning on using AM for the manufacturing of their components and this trend will continue to increase once AM parts establish themselves through upcoming pilot projects and increased adoption in existing NPPs. SMRs will be able to utilize many of the benefits of AM including increased geometry complexity leading to greater efficiency, decreased weight and smaller parts.

If AM adoption in existing NPPs becomes a viable option in the coming years SMR reactor designers can increase their dependence on “designing for AM” expanding the use of AM parts in the initial design phases instead of only for replacement parts as is the case with existing CANDU units. This will allow for SMR designers to provide safer, smaller, more efficient reactors from the beginning while keeping costs low further cementing Canada as a leader in the nuclear space.

AM parts have many other uses in the nuclear field such as being used in major component replacement simulation environments. While AM parts have the ability to innovate the nuclear space and can provide a number of advantages, it is not always the best manufacturing method. A sample flow chart can be seen in Exhibit E which shows when there is and when there isn’t a business case for additively produced parts.

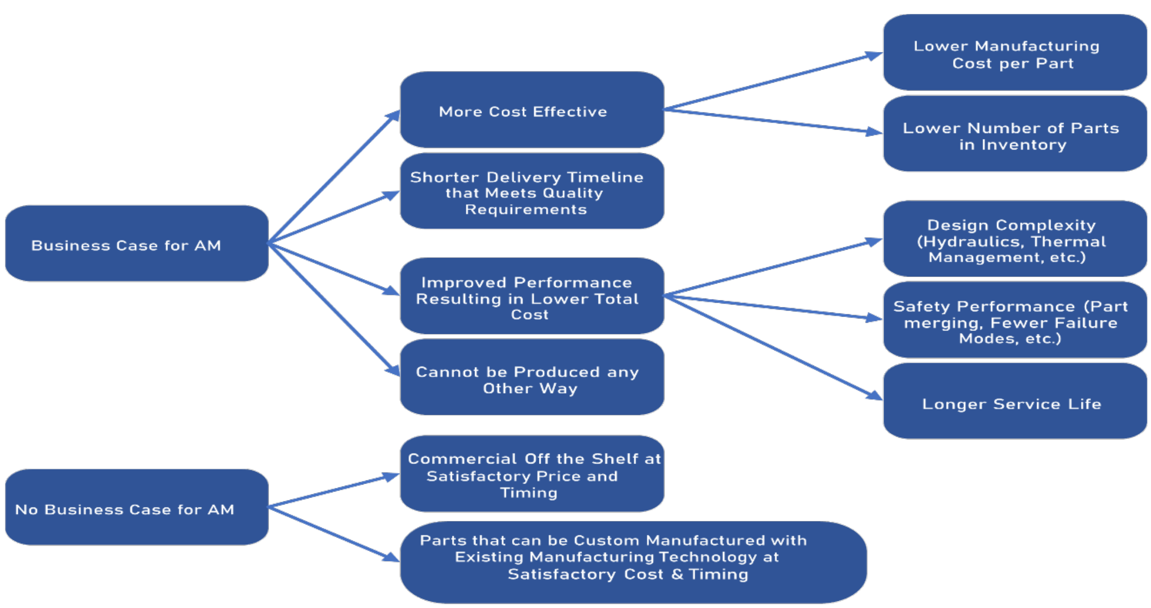

Exhibit E: Analysis of the Opportunity for AM based on types of Equipment and Components including categorization by the realized benefit

E. Future Development

This roadmap outlines the implementation of advanced manufacturing in Canada's nuclear industry and sets out a step-by-step approach, building one success after another. However, getting over the inertia for the first few applications will be the most critical step to ensure success. Experience for AM in the nuclear space must be built up following a well-thought-out plan involving manufacturing many parts of increasing quality levels. Projects such as the ones described in the remainder of this report will work to install nuclear components first starting at quality level 4 and increasing in quality level as experience is gained until quality level 1 parts and pressure boundary components can be manufactured and installed. Further progression will be required to develop reactor core parts which will require comprehensive experience gained through previous AM installations and pilot projects.

Advanced Manufacturing Quality Program

As is the case for conventional nuclear component manufacturing technology, an AM quality management program is essential and must be comprehensive and include capabilities for the following elements:

- Part testing including:
    - Non-destructive testing
    - Coupons for destructive testing
- A comprehensive and documented quality program that covers each of the AM process chain steps
- Qualified test lab for metrology, microscopy, chemical, and mechanical testing
- Certification for part production by auditors against CSA N299.x in Canada or other relevant programs (e.g. for non-safety parts, one option is TÜV Süd certification of manufacturers of 316L pressure boundary parts made by laser powder bed fusion).
- Production track record to demonstrate and confirm process stability and reproducibility
- Participation of AM experts in standards development (e.g. ASME, ASTM, ISO, CSA, API)
- Compliance with these standards in supplying AM components for nuclear applications.

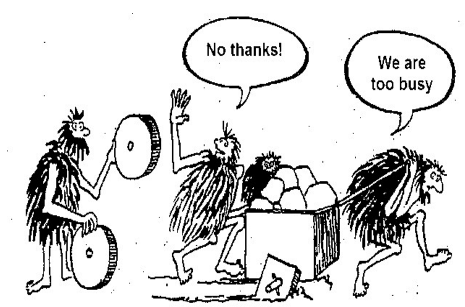

Exhibit E: Innovation Tendencies

It will be important for suppliers and end-users (nuclear utilities) to work collaboratively on some initial applications and then jointly to map out which additional components or parts can be made by AM over time. This approach, as outlined in this AM roadmap, will determine the timing and the amount of required investment in capacity, facility, equipment, etc.

F. Pilot Project

The following project approach is intended to provide a rapid advancement of the use of additive manufacturing for the Canadian nuclear industry. It is complementary in nature to longer-term ambitions to grow adoption of AM-methods within the industry.

Three Stage Implementation plan (Kinectrics & Burloak)

Kinectrics and Burloak have developed a 3-stage plan to produce, qualify, and deliver parts or assemblies using additive manufacturing methods for Canadian nuclear facilities (including CANDU reactors). This process will aim for rapid deployment using Kinectrics' well-established approaches for reverse engineering and commercial grade dedication. Standards bodies, regulators, and other stakeholders will be consulted through the existing committees and interfaces throughout the process.

The 3 stages for the project are as followed:

Phase 1: Simple Application

Manufacturing, testing/qualification, and delivery of a Quality Level 3 or 4 part for an operational reactor

Phase 2: Increased Safety

Manufacturing, testing/qualification, and delivery of a Quality Level 2 level part for an operational reactor

Phase 3: Pressure Boundary

Manufacturing, testing/qualification, and delivery of a Quality Level 1 level part for an operational reactor

Each of these phases will be subjected to quality checks above and beyond those of traditionally manufactured parts to assure the safety of the components. Each phase will involve first selecting a part within the respective category, then obtaining or creating a CAD model for the part using reverse engineering methods. Next, Burloak will utilize their Oakville facility to print the part and Kinectrics will conduct all required safety qualifications a traditionally manufactured part would be subjected too as well as additional safety tests to confirm the part will not compromise safety. Once all tests have been conducted and the part is qualified it will be installed into a plant and observed. This process will be thoroughly reviewed and reported on by the Kinectrics and Burloak teams to identify any areas of improvement for each subsequent stage. A process flow can be seen in Exhibit G.

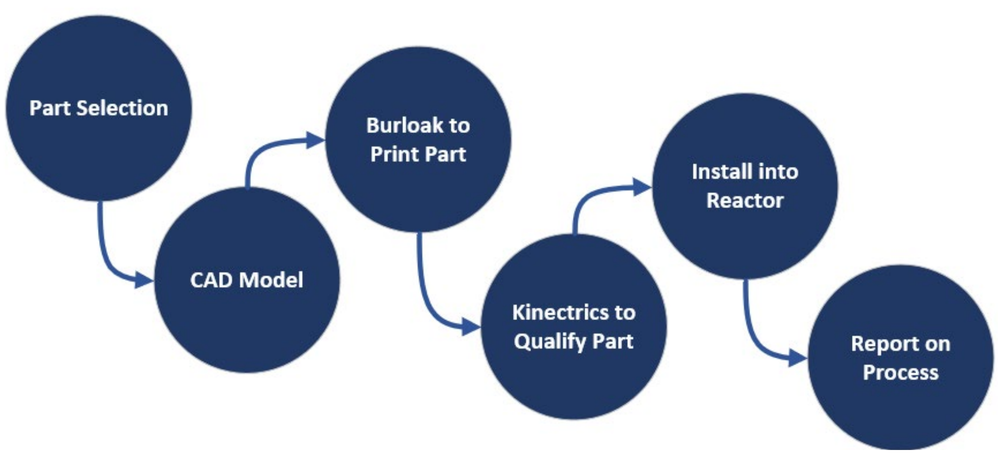

Exhibit F: Kinectrics and Burloak Pilot Project Process Flow

The most important part of this exercise will be the qualification process as this will test whether AM parts can provide the same or better quality than traditionally manufactured parts. In order to instill confidence in the AM process, the first test cases will undergo an added level of scrutiny and be subjected to extra testing not required in the usual qualification process. This qualification process will depend on the part chosen but could include a variety of safety tests such as:

- Thermal and radiation ageing
- Seismic and vibration simulations
- Cyclic ageing
- LOCA testing
- Electromagnetic / Radio Frequency Interference

The additively manufactured part will also be subjected to the same material documentation review and traceability requirements as traditional parts. These tests and documentation reviews will demonstrate a high degree of confidence that the AM parts will perform to the same degree as a traditionally manufactured part.

Near Term Objectives

- Phase 1 part installation – Q1 2022
- Phase 2 part installation – Q3 2022
- Phase 3 part installation – Q1 2023
- Report on pilot cases- Q2 2023
- AM fully integrated into Nuclear supply chain – Q3 2023

Near-term adoption of AM in the nuclear industry is necessary to build trust within the industry on the quality and performance of AM parts. The nuclear industry is one where failure of even one part is not an option.

G. Ten Year Vision

Year One– Conduct pilot AM project to supply and install AM parts in a Canadian nuclear facility in non-safety critical areas

Year One/Two – Expand pilot to a safety-related and high criticality part (e.g., pressure boundary)

Year Two/Three – AM regularly considered for part procurement

Year Three/Four – AM used for increased part complexity and part consolidation (Also useful for SMRs)

Year Four/Five – Digital part warehouse accessible to industry suppliers for reference

Year Five/Six – Incorporation of Operating Experience into codes and standards, with guidelines for application of AM in nuclear industry

Year Six– Increased research into nuclear-specific AM applications that may allow for expanded use (e.g., niche applications in fusion technologies, nuclear harsh environments,)

Year Eight– AM is a viable option for large-scale parts (e.g., pressure vessels, heat exchangers)

Year Eight to Ten and Beyond – New nuclear technologies including SMRs utilize AM parts to reduce manufacturing timelines, complexity and improve economics

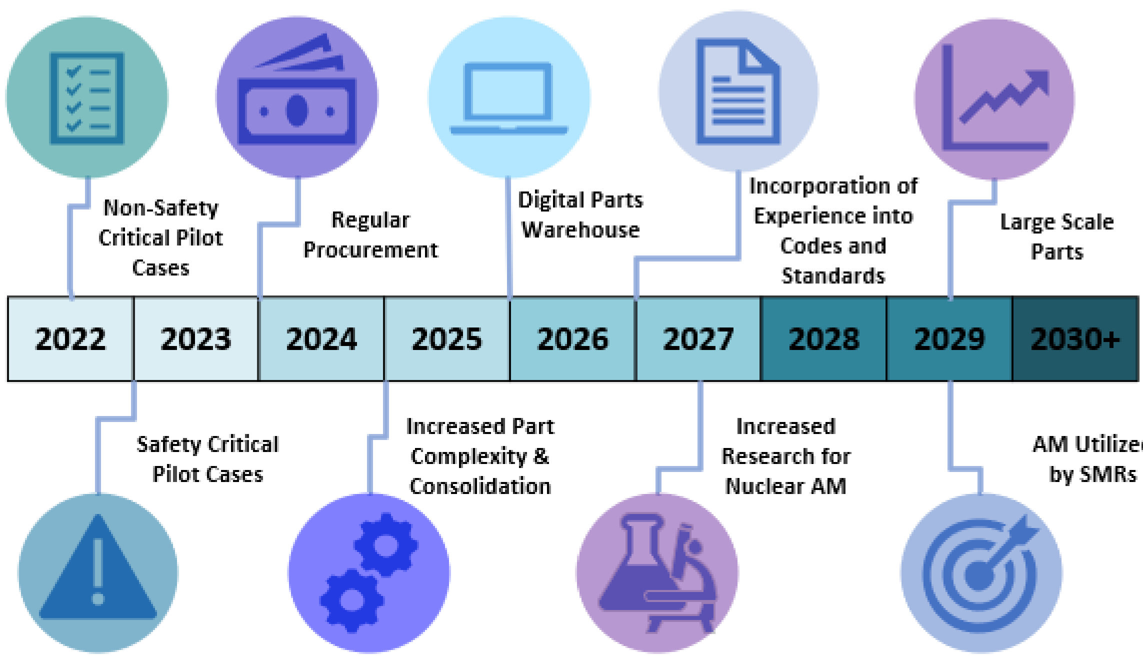

Exhibit G: Ten Year Vision

H. Next steps to end 2021 and 2022

Below are near-term tasks that OCNI, KSB, Kinectrics and industry partners will undertake to build knowledge and capabilities in AM among Canadian nuclear utilities, the nuclear supply chain, and SMR developers.

Task One: build Nuclear AM Alliance

OCNI
CNL
OPG X-Lab
NII
Kinectrics
Burloak
Promotion
MDA
AMC (Advanced Manufacturing Consortium)

Task Two: Stakeholder Engagement Mapping and Awareness Building

- Nuclear Utilities
- CANDU suppliers
- AECL / CNL
- SMR developers
- SMR suppliers
- Regulators
- Standards organizations
- COG CANDU Inspection Qualification Bureau (CIQB)
- Academic AM centres (e.g. AMC, UW's MSAM and new AMA)

Previous Awareness Building

- OCNI Advanced Manufacturing Seminar and Exhibit -Apr. 16, 2019
- OCNI Advanced Manufacturing Forum -Nov. 10/11, 2020
- COG/CNL Advanced Manufacturing Workshop -Mar. 19, 2021
- GAIN/EPRI/NEI Advanced Methods for Manufacturing- Qualification Workshop -Aug.24/25, 2021
- GIF AMME Workshop on Advanced Manufacturing Modeling & Simulation- Nov. 8/9, 2021

Task Three: secure partners, location, funding for **"Canadian Nuclear AM Training and Test Center" Key events for AM in Nuclear Awareness Building:**

February 2022 - AM Workshop with key stakeholders (Utilities, AECL, CNL, SMR developers, AM centres)

June 2022 – Grand Opening of the McMaster Manufacturing Research Institute (MMRI).

Third Quarter 2022 – University of Waterloo – Industry Open House at Advanced Manufacturing Facility

Date TBD 2022 – GIF AMME Workshop on Advanced Manufacturing Qualification of AM for Nuclear Components

I. Conclusion and Call to Action

The Canadian nuclear industry has historically been cautious in the adoption of new technologies.

The Canadian nuclear industry now faces two challenges that require innovation and bold action:

- The Darlington and Bruce reactors must operate safely and efficiently until 2060 and beyond supported by a strong Canadian supply chain capable of reverse engineering, manufacturing, and supplying obsolete components.
- A new generation of SMRs and perhaps conventional reactors must be cost-effective and efficient and integrate with renewable energy sources.

These dual challenges can be met by innovative approaches to plant maintenance and new plant construction. The adoption of advanced manufacturing technologies by the nuclear sector, following the lead of other industries like aerospace, will ensure that these dual challenges can be overcome.

This Advanced Manufacturing Roadmap lays out a path for the adoption of Advanced Manufacturing technologies by the Canadian nuclear industry.

J. References

1. General Electric, Additive Manufacturing | Aviation and aerospace industry, https://www.ge.com/additive/additive-manufacturing/industries/aviation-aerospace
2. Tomas Kellner, This Factory Is 3D Printing Turbine Parts For The World's Largest Jet Engine, https://www.ge.com/news/reports/future-manufacturing-take-look-inside-factory-3d-printing-jet-engine-parts

Appendix A: Impact on Standards: Worked Example of AM Valve for Darlington to verify Standards Applicability

CSA Advanced Manufacturing Task Force

Recognizing the potential of standards to foster and enable innovation, CSA conducted a strategic session in late 2019 to prioritize innovation areas of relevance to CSA standards and Canadian nuclear sector, where AM was identified as one of the priority areas. An AM task force was established to review the use of advanced techniques, technologies, and materials, including additive manufacturing ("3D printing"), new welding techniques, coatings, and cladding and impacts on standards.

The purpose of the task force was to consider the current and potential future states for AM technologies and their application, examine the path for adoption of AM technologies in Canadian nuclear applications, identify the relevant existing CSA Nuclear standards, and identify standards gaps and propose recommendations to facilitate acceptance of AM methods.

To ensure that the viewpoints of a variety of stakeholders impacted by the use of advanced manufacturing is considered, the membership included representatives of Canadian utilities, Suppliers, Regulator, Research organizations.

The task force identified key areas of focus, mapped relevant CSA standards, and assessed potential impacts to standards. The task force also conducted landscape scan of existing standards of AM related standards including NEI's *Roadmap for Regulatory Acceptance of Advanced Manufacturing Methods in the Nuclear Energy Industry* (May 2019)*,* America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC) *Standardization Roadmap for Additive Manufacturing* (June 2018), and ISO/ASTM 52910:2017, *General guidelines for design for AM*.

Identified topics that may impact related standards include:

a) design of parts
b) qualification of manufacturing process and of new items,
c) material requirements,
d) acceptance requirements,
e) inspection requirements, and
f) aging management requirements.

The relevant CSA Technical Committees reviewed the findings and determined that no critical barriers were identified, however also identified areas for improvement (e.g., additional guidance) within existing impacted standards. These gaps will be addressed as the impacted standards are updated.

KSB/OPG Worked Example

An industry case study of an example walkthrough for use of AM for a safety-related component (e.g., a pump part) in a nuclear power plant is being conducted to assess the impact on standards and identify any potential gaps. This work will entail reviewing standards required for the design, manufacture, and obtaining approval for the use of a safety-related component manufactured using AM techniques. It is anticipated this will benefit industry/suppliers by illustrating a pathway for use of an AM component in the Canadian context, and to help identify any challenges or gaps in standards/requirements.

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Additive Manufacturing Case Study:
48-Hour Impeller Replacement at a Nuclear Power Plant

Nuclear power plant operators face the daily challenge of managing obsolescence by maintaining sizable spare parts inventories or urgently procuring (or borrowing from another plant operator) critical replacement parts. In addition, Small Modular Reactor developers need to focus on equipment cost reductions, shorter delivery timelines, and novel/compact component designs that are difficult to manufacture by conventional casting or machining.

Additive manufacturing (AM) offers current and promising solutions to all these challenges. As shown in this case study , additive manufacturing can be used to manufacture parts much more quickly (and often more cost effectively) than traditional manufacturing. Additive manufacturing can also produce parts with complex shapes to improve equipment performance, functionality or safety that otherwise cannot be made with conventional manufacturing methods.

How to get a custom precision-manufactured part
for failed equipment delivered to your plant within 48 hours?

Challenge:

- Situation: A French nuclear power plant (NPP) needed an impeller urgently; an auxiliary loop pump would be out of service until the impeller could be replaced.
- Obsolete part: The failed pump was obsolete and spare parts were no longer available.
- Alternatives:
    1. replacing the entire pump would require reengineering with months of time and effort;
    2. a new impeller made by casting with delivery in ~ 8 weeks;
    3. a new impeller produced by additive manufacturing.

Option 3 was clearly the best option.

 1

Solution:

- KSB delivered two additively manufactured impellers in 48 hours. One impeller was put into service immediately, and the other used as a spare.
- Material was upgraded to proprietary KSB Noribeam® 316L from the original cast iron, providing upgraded performance and longevity.
- Quality control: The NPP's acceptance focused on KSB's quality control certification. KSB has had a rigorous and comprehensive additive manufacturing quality management process in place for many years which the NPP was able to use to verify the quality plan. A prior validation and part acceptance was completed by the NPP's design office. Since the pump was installed years ago with no subsequent changes or upgrades, part acceptance could be managed in a short timeframe.

KSB Company
80,204 followers
1mo •

Two of the very fast troops: the reverse engineering team in Pegnitz produced an impeller for a nuclear power plant in record time. The 3D design was made, the raw part was printed, machined, tested and taken by taxi to its destination - all in just 48 hours! #KSBteam

The Additive Manufacturing process from start to finish:

1. Develop the required quality CAD design file
2. Alloy selection appropriate for the application
3. Print the parts on a laser powder bed fusion machine using qualified printing parameters
4. Post processing
5. Testing
6. Quality control
7. Produce quality control documentation
8. Delivery to the customer

All possible in 48 hours.

ZERTIFIKAT

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91257 Pegnitz

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verfügt und dieses anwendet.

Der Geltungsbereich ist aus der Anlage 1 ersichtlich.
Weitere Einzelheiten sind im Bericht Nr. 600 129 713 genannt.

Das Unternehmen ist daher berechtigt, in Übereinstimmung mit der Druckgeräterichtlinie 2014/68/EU Bescheinigungen über spezifische Prüfungen an den Werkstoffen im o.g. Geltungsbereich auszustellen. Eventuell weitergehende Anforderungen aus den angewandten technischen Spezifikationen zur Erfüllung des Anhanges I bleiben unberührt.

*Die Fertigung erfolgt auf pulverbettbasierten Laserstrahlmaschinen

Zertifikat - Nr.: DGR-0036-AM-001-19

München, 31. Oktober 2019

KSB first to achieve certification for pressure boundary parts made by additive manufacturing

1.4404 (316L)

Certification process by TÜV Süd included rigorous review of:

- Company
- Material
- Machine
- Print location on the build platform
- Print orientation
- Print parameters
- Test coupons for destructive verification
- …

https://www.tuvsud.com/en/press-and-media/2019/august/tuv-sud-issues-first-ever-certificate-for-additive-manufacturing-of-materials

Appendix C Fabrication Cost Comparison Additive vs Conventional Methods

A Cost comparison will depend on:

- Whether it is the same design in additive as conventional or a different design
- Number of units
- Whether the time required for sourcing from conventional manufacturing is an issue

Generalizations about manufacturing technologies:

- Machining can be costly, especially if a lot of material needs to be machine, the material is difficult to machine, and the geometry limitations of internal features (straight lines rather than curves) result in a sub-optimal design
- Casting is often very cost-effective, but casting is very expensive to set up for a unique part
- AM benefits are often created due to time reduction, inventory reduction and optimized design (not printing the same design as conventionally manufactured); benefits also are from rapid design development and rapid prototyping

Cost comparison possibilities:

- AM could be less cost to produce the same part compared to conventional manufacturing
- AM could allow for less inventory to be held
- If AM part has improved performance, this needs to be accounted in the cost comparison, for example:
    - Thermal performance
        - Better heat transfer by optimization of geometry, wall thickness or material
    - Hydraulic performance
        - Better hydraulic performance by geometry optimization
    - Safety performance
        - Safety benefits by reducing failure modes, e.g. by part merging or optimization of hydraulic or corrosion performance
    - Longer service life
        - Due to optimized design
        - Built in maintenance or monitoring functionality

Additive manufacturing cost considerations:

- Complex designs are the same cost as simple designs
- Build time (time to print) on the AM machine (time on the machine is a significant cost component, as the machines are expensive)
    - Overall outer dimensions
    - Volume of material printed
- Material cost (AM powders have a range of costs)
- Post-processing cost
- Number of units fitting into one build job
- Development costs (design, parameter development, iterating, testing, etc), once established then the cost is just the material printing and post processing

SMR cost saving considerations may be different for:

- FOAK parts
- Building 1 vs. 10 parts
- Repeat builds

AM Cost savings example (84% in example below):

AM can lower costs for serial production. KSB was externally sourcing a machined part, a mechanical seal flush connection. We wanted to find out if we could produce it ourselves by AM, with the same quality but at a lower cost. We redesigned the part, but still fitting in the same way so that no changes were required to the pump. We were able to achieve a cost savings of 84%.

One of the keys to the cost savings is how to use AM. One aspect was the redesign, as shown in the previous slide. The other aspect is how to build it. Here is the configuration on the AM build plate, maximizing the available space, and minimizing the support structure. This orientation at an angle reduces post processing costs. We now save over 84% making this part ourselves compared to purchasing it.

	Now	Mid-term	Long-term
Parts not in direct service			
Prototyping - Rapid design iteration - Proof of concept tests - Display models	X	x	x
Test rigs - Parts, components, equipment, jigs, fixtures	X	x	x
Parts in use in the operation			
Irradiated – pressure boundary			x
Irradiated – non-pressure boundary		x	x
Safety – pressure boundary		x	x
Safety – non-pressure boundary	x	x	x
Non-safety – pressure boundary		x	x
Non-safety – non-pressure boundary	x	x	x

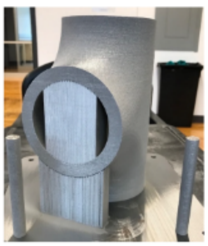
Source:
COG / CNL Workshop on Advanced Manufacturing March, 2021
Marc Albert
Senior Technical Leader
Advanced Nuclear Technology (ANT)
www.epri.com

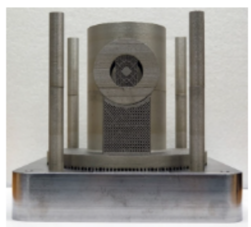
EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Additive Manufacturing Qualification for Nuclear Applications

- Develop and demonstrate innovative qualification strategy/approach
  - Incorporate Integrated Computational Materials Engineering (ICME) and in-situ process monitoring
- ASME Code Case for additively manufactured 316L via LPBF
- Focused on laser powder bed fusion only

DOE Project DE-NE0008521





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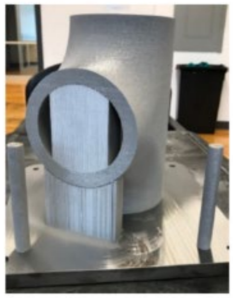
Oak Ridge National Laboratory
Managed by UT-Battelle for the U.S. Department of Energy
The University of Tennessee Knoxville
Auburn University Samuel Ginn College of Engineering
oerlikon am

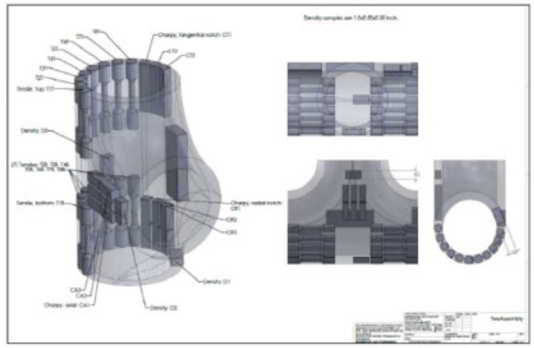
AM Qualification for Nuclear Applications
--ASME Data Package Development

- 3 different LPBF machine models
  - EOS M280, EOS M290, Renishaw 250
- 4 different vendors/suppliers
- 4 sets of processing parameters
- 4 different 316L powder heats
- 3 different components (next slide)
- Different build environments --argon and nitrogen
- Components are >8-inches in diameter and ~0.5-inch thick
- Two conditions: HIP and SA; SA only
- Vertical control/witness samples included
- Parameter data sheet recorded for each build

Renishaw AM 250 System
Courtesy: ORNL/Renishaw

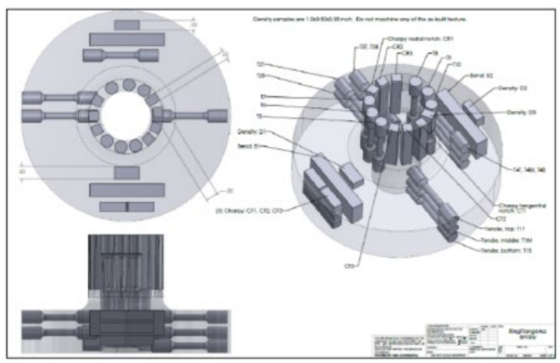
Pipe Tee Section – Auburn University





4-1/8" wide x 8-1/4" tall
(105mm wide x 210mm tall)

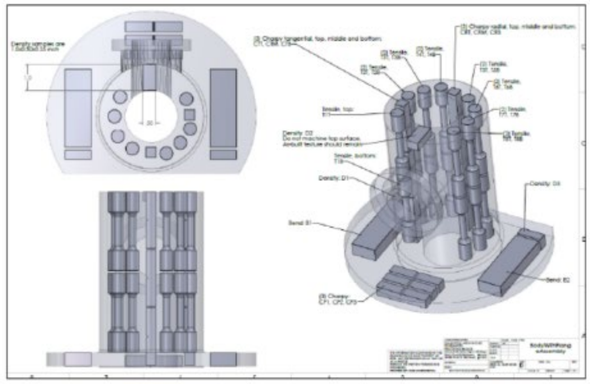
Ring Flange End Connection – Westinghouse



8.5" Ø x 1.5" thick x 2" bore
(216mm Ø x 38mm thick x 51mm bore)

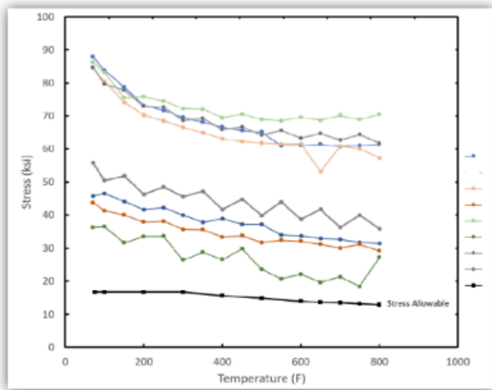
Gate Valve Body – Oerlikon

8" Ø x 2" bore x 4" OD x ½" thick
(203mm Ø x 51mm bore x 102mm OD
x 13mm thick)



Summary of Data Package Contents

- Data package with mechanical and microstructural results:
  - Chemical analysis (both pre and post printing)
  - Microstructure analysis
  - Process parameters
  - Heat Treatment data
  - Hardness
  - Tensile (yield and UTS)
    - including elongation & reduction in area
  - Toughness (Charpy testing)
  - Fatigue Data
  - Weld data



Draft ASME Section III Code Case for AM 316L using LPBF

- Summary of Code Case Contents
  - Design stress intensity values and maximum allowable stresses
  - Heat Treatment
  - Powder to ASTM F3184
  - Essential LPBF build variables (*proposed*)
    - Layer thickness
    - Laser power
    - Focus settings
    - Beam diameter
    - Effective velocity
    - Scan strategy
    - Stripe width
    - Hatch spacing
    - Shielding gas composition and flow
  - Witness samples and test specimen requirements
  - Examination techniques
  - Pressure testing requirements
  - Neutron dose limits

Record 20 254

DRAFT Code Case XXXX
Austenitic Stainless Steel (UNS S31603)
Section III, Division 1 – Subsection NB/NC/ND, Class 1, 2 and 3 Components

Inquiry: May UNS S31603 that meets the specification requirements of ASTM F3184-16 for additively manufactured stainless steel products produced using the laser powder bed fusion process, then hot isostatic pressed and solution annealed, be used for Section III, Division 1 – Subsection NB/NC/ND, Class 1, 2 and 3 components construction?

Reply: It is the opinion of the Committee that UNS S31603 conforming to ASTM F3184-16 for additively manufactured stainless steel products produced using laser powder bed fusion, then hot isostatic pressed and solution annealed, may be used for Section III, Division 1 – Subsection NB/NC/ND, Class 1, 2 and 3 components construction provided the following additional requirements are met:

Code Case Record No: 20-254

Summary – ASME Code Case & Data Package

EPRI-DOE Technical Report: 3002018273

- Three components, four builds performed
- >0.50-inch thick components (for testing)
- All builds provide acceptable microstructural and mechanical properties
- Good fatigue properties
- Stress Allowables developed
- Weldment data included in data package

What's Next?
ASME Code Case balloting, comments & resolution support (ongoing)
Regulatory Approval – additional data required?

Appendix F Advanced Manufacturing and Material Science for reducing CANDU Outages (COG/CNL))

Canadian Nuclear Laboratories (CNL) has been contributing to COG's Strategic R&D (SRD) Reduced Outage (RO) program by investigating how advanced manufacturing technologies could be used to reduce the cost, duration, and personnel dose associated with CANDU reactor outage maintenance. Many CANDU reactors in service today have been in operation since the 1970s and equipment obsolescence is an increasing, challenging problem. The use of advanced materials and fabrication techniques could play a key role in the future of nuclear maintenance by offering timely, cost-efficient, and reliable replacement of aging and obsolete parts. There is significant opportunity to utilize these alternative fabrication technologies to reduce outage but the specific areas need to be identified and evaluated. Thus the objective of this program is for key researchers to work with outage, site engineering and equipment reliability personnel to identify promising opportunities where these technologies could make significant improvements – from elimination of long lead / obsolete items, to quick printing of a solution to avoid forced or extended outages, to new parts with improved material properties or even built-in diagnostic capabilities. This research is exploring these new technologies and related material science issues behind them to develop a strategic plan and program for realizing their promising potential applications in CANDU plants.

As part of this innovative work, a State Of The Art Report (SOTAR) is being compiled to investigate advanced manufacturing technologies (AMTs) and identify areas that CANDU reactors may benefit from their applications. The team is collaborating with various CANDU reactor facility groups, to identify opportunities of interest where AMTs could be implemented for outage reduction. Key quality requirements are being identified to ensure that AMT research and procurement for a Canadian nuclear facility are aligned such that parts produced via an AMT have the requisite pedigree to perform in the intended application. Notably, common engineering materials such as 316L produced by additive manufacturing are being evaluated where their improved corrosion properties could provide benefit in areas of the stations where current material selections lead to higher corrosion rates. In addition, this work has identified several areas of interest where the elimination of dissimilar metal welds may lead to a reduced outage inspection burden. Figure 1 shows an example of how additive manufacturing can be used to eliminate weld locations entirely.

Figure 1 – An example of how additive manufacturing can eliminate weld locations in a pipe manifold [F.1].

CNL held an Advanced Manufacturing Workshop in March 2021 which informed interested parties of a selection of AM applications, followed by discussion on a variety of AMT related topics, ranging from obsolescence to embedded diagnostics. Key networking connecting were established as a result of this workshop, which has provided pathways to groups of interest related to the program.

The goal extending beyond this initial work is to conduct pilot projects to fabricate and test suitable CANDU components, acting as proof of principles, technology demonstrations, and allowing for performance evaluations. The business case can then be evaluated with areas of success and improvement highlighted for future research.

References:

[F.1] MTI Albany, "Turbo Collector Project | Leading Additive Manufacturing Companies in Stainless Steel 3D Printing", April 29, 2016, url: http://www.mtialbany.com/tag/additive-manufacturing/

Appendix G(a) Framatome /KSB AM Fuel Assemblies

KSB Press Release November 2020

"Cooperation in additive manufacturing

The KSB Group and Framatome in Germany are working together in the field of additive manufacturing. The aim of this cooperation is to draw on the experience the pump and valve manufacturer has gained in the certification process for pressure-retaining components made by additive manufacturing and use it in the environment of reactor applications.

The companies are jointly working on a range of topics from the qualification of feedstock to nuclear applications and right through to the manufacturing of components.

At its Pegnitz site KSB has built up a high level of expertise over the last few years in powder bed laser melting regarding the quality achieved, the process know-how and the test methods used.

The German company Framatome GmbH in Erlangen is mainly specialized in servicing and modernizing nuclear power stations in Germany and other countries."

framatome

Additive Manufacturing

Enhancing the performance of fuel assemblies

New component designs without limits

Challenge

The conventional manufacturing technology limits design freedom and implementation. Designers of the components are highly depending on manufacturability – not only for Lead Fuel Assembly, but also for reload quantities.

Solution

In our labs, Additive Manufacturing has already surpassed this limitation. Structural components, such as upper tie plate grids, are manufactured by Selective Laser Melting. The material for this new upper tie plate grid (see picture) has already been tested in regard to its mechanical behavior and corrosion under out-of-pile conditions.

The outcomes of these material tests were excellent. As a result, we are now preparing to test the material under in-pile conditions in a commercial nuclear reactor – exposing it to coolant as well.

To improve filter efficiency and thus fuel reliability, a new generation of anti-debris filters is currently under development, utilizing all the possibilities provided by Additive Manufacturing.

In order to provide you with the best solutions, we have been carrying out various Research and Development programs to cover all kinds of fuel components for Light Water Reactors as well as Research and Test Reactors.

3D printed upper tie plate grid

Technical information

- Current focus on stainless steel and Nickel based alloys
- Maximum part sizes is 300 x 300 x 300 mm³
- Quality is assured by industrial computed tomography inspection

Outlook

- In-pile testing of printed samples made from stainless steel and Nickel based alloys will begin in a reactor in 2019
- Lead quantities of upper tie plate grids to be available by 2021

Customer benefits

- Significant performance gain in the fuel assembly
- Time to market of components reduced by a factor of up to 20
- Number of component parts reduced by a factor of up to 100
- Customized quantities and designs of components

Your performance is our everyday commitment

Contact: sales-fuel@framatome.com
www.framatome.com

https://www.framatome.com/solutions-portfolio/docs/default-source/default-document-library/product-sheets/a1718-p-ge-g-en-201901-additive-manufacturing.pdf?Status=Master&sfvrsn=4359198_2

https://www.euronuclear.org/archiv/topfuel2018/fullpapers/TopFuel2018-A0180-fullpaper.pdf

Appendix G (b) Westinghouse Advanced Manufacturing and Reverse Engineering Development for Replacement Parts

Westinghouse Non-Proprietary Class 3

 1

WAAP-12093

Westinghouse

WESTINGHOUSE ADVANCED MANUFACTURING AND REVERSE ENGINEERING DEVELOPMENT FOR REPLACEMENT PARTS

ASME ICONE 28

Advanced Manufacturing Panel

August 4, 2021

Clint Armstrong: armstrcb@westinghouse.com
Advanced Manufacturing Subject Matter Expert
Westinghouse Global Innovation

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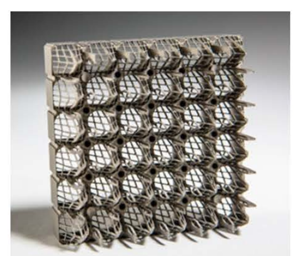
WAAP-12093

Westinghouse Advanced Manufacturing Program Objectives

Improve industry competitiveness, through the development and implementation of advanced manufacturing technologies

- Drive cost reductions in component manufacturing
- Enable new products and services that provide innovative customer solutions
- Leverage collaborative development and external funding sources



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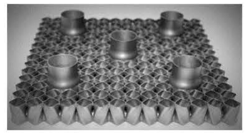
Additive Manufacturing (AM) Objectives

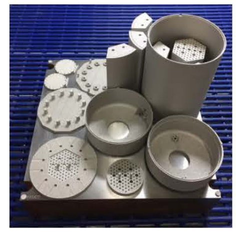
Exploiting the Benefits of Additive Manufacturing Technologies

- Producing components with: Powder Bed Fusion (PBF), Binder Jetting (BJ), and Directed Energy Deposition (DED) AM technologies
- Complex components required for performance gains
- Advanced reactor components – eVinci™, LFR
- Obsolete and high value / lead-time components
- Tooling / jigs / fixture, prototypes, mockups




Enabling AM for Nuclear Component Construction

- Leading material development & testing for in reactor use, including irradiation and PIE of 316L, 718 and Zirc-2
- Supporting the development of ASTM and ASME codes and standards
  - Submitted first Laser PBF ASME Code Case in August 2020

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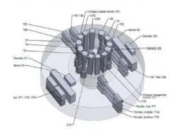
Qualification Paths

Pressure Retaining, Safety Related Components

- Submittal of AM Code Cases and support of ASME's advanced manufacturing groups

Non-Pressure Retaining, Safety Related Components

- Design & Specification updates, Commercial Grade Dedication, NRC 10 CFR 50.59

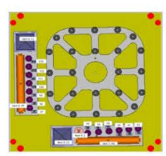


Non-safety Related

- Design & Specification updates

Thimble Plugging Device (TPD) selected as first component to test in core

- Low risk component, moderate complexity
- Produced hybrid 304/316L TPD
  - Manufacturing qualification……..2017-2018
  - Production units…………………2018-2019
  - Delivered Byron 1………………..Spring 2020




Westinghouse

Replacement Parts: Reverse Engineering of Obsolete Castings

Reverse Engineering Process Overview – RES Motor Bearing Bracket

Laser scanning → 3D modeling → AM sand molds → traditional casting

Westinghouse Non-Proprietary Class 3
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WAAP-12093

Reverse Engineering Benefits for Replacement Parts

Significant lead-time reduction

Potential cost reduction

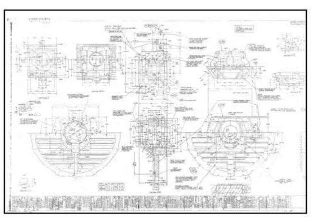
- Dependent on current cost, tooling availability, and part size, complexity and quantity

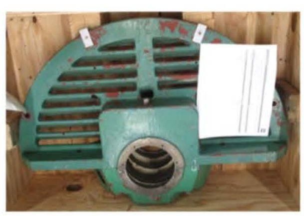
Short-term opportunity to gain AM benefits for safety related components

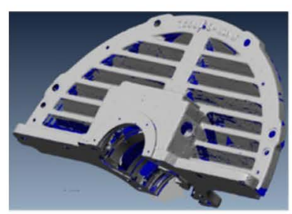
- AM complexity with traditional sand casting

Conversion of outdated, illegible drawings to digital design / information

Developed template Commercial Dedication Instruction (CDI) for dedication of legacy casting







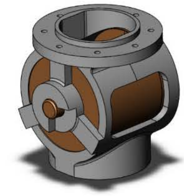
Addressing Part Obsolescence for Nuclear Applications

Collaborative Demonstration Project

- Collaboration with Concurrent Technologies Corporation
- 24-month project, funded through a PA manufacturing grant*

Demonstration Components

- Flap and flap housing
- Westinghouse split sleeve bearing bracket
- 1” globe valve
- Westinghouse breaker cover

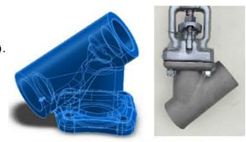


420 SST / Bronze Binder Jetting

Binder Jetted Sand Casting Molds

Traditional Bronze Casting

* This Project was financed by a grant from the Commonwealth of Pennsylvania, Department of Community and Economic Development (DCED).



Laser PBF 304L & 316L SST

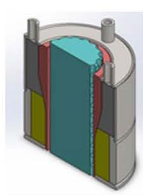
Binder Jetted Sand Casting Molds & Traditional Cast Iron

PC and Ultem FDM

Westinghouse Implementation Efforts

Replacement Parts Identification Efforts

- Currently working to identify, demonstrate and qualify AM applications
- Data and expert review for application down-selection
- Development of detailed cost estimates / business cases for top candidates
- Utilizing laser scanning and reverse engineering software to develop editable 3D models for obsolete parts



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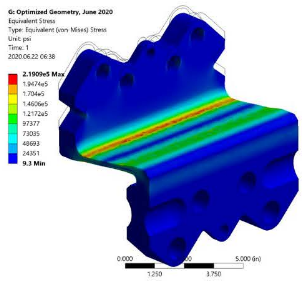
Design for Additive Manufacturing – Topology Optimization Example

Salem Thermal Shield Flexure – Advanced Manufacturing Demonstration

- Completed topology and AM optimization efforts
- Successfully complete fatigue testing of topology optimized AM flexure
  - Met fatigue testing requirements



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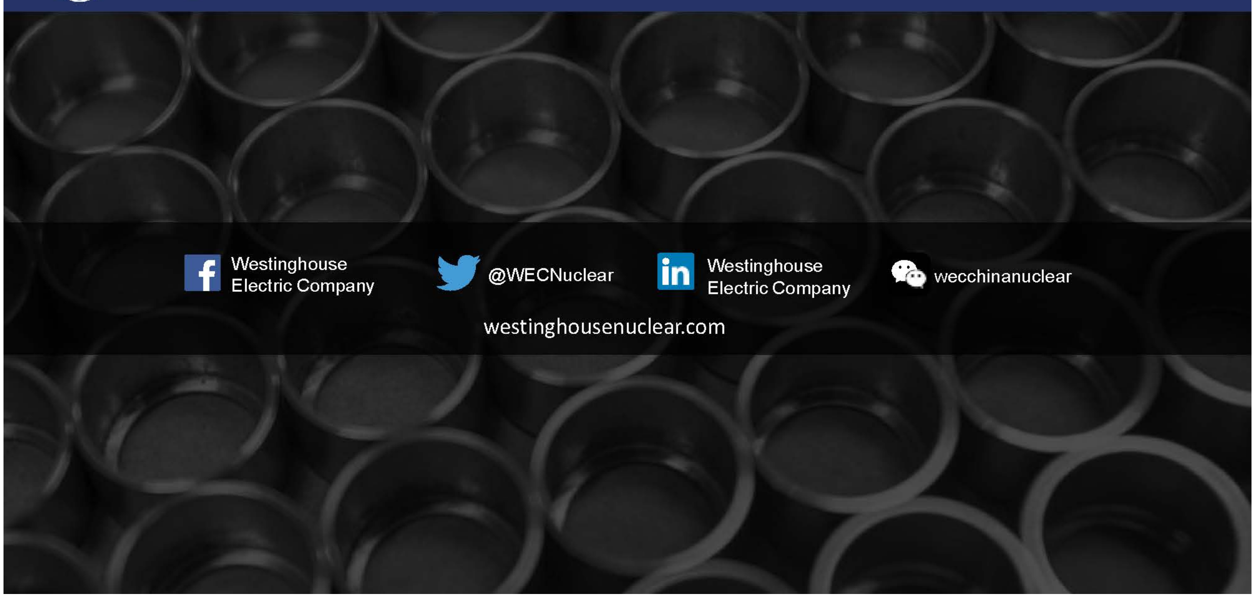

Appendix H Burloak Technologies and Kinectrics to Develop Additively Manufactured Parts for the Nuclear Power Industry (News Release August 18, 2021)

Burloak Technologies and Kinectrics to Develop Additively Manufactured Parts for the Nuclear Power Industry

OAKVILLE, ON, Aug. 18, 2021 /CNW/ - Burloak Technologies Inc., a division of Samuel, Son & Co., Limited, and Kinectrics are pleased to announce a collaboration agreement to develop additively manufactured parts for the global nuclear power generation industry.

Under the terms of the agreement, Burloak and Kinectrics will join forces to optimize the design and manufacturability of a range of components and replacement parts for a range of applications used in the nuclear power generating process. The two companies will jointly qualify all components developed under the partnership and work together to accelerate adoption of additive manufacturing within the nuclear power industry.

"The nuclear power generation industry has exacting performance and reliability requirements because reactors simply cannot fail," stated Martin Baxendale, Vice President of Operations at Burloak. "We look forward to working with Kinectrics to leverage our collective knowledge to offer performance and cost benefits to nuclear operators."

"Kinectrics looks forward to working with Burloak to bring additively manufactured safety-critical parts to the global nuclear power generation industry with increased quality, shorter lead times, complex geometries, and a lower overall cost of ownership," said David Harris, President and CEO of Kinectrics. "Burloak's experience in the global additive manufacturing industry, coupled with Kinectrics' extensive nuclear experience and deep understanding of materials, testing, codes and standards, nuclear regulation, and safety critical applications, will offer its clients innovative solutions for plant obsolescence issues and new options for Small Modular Reactors."

Kinectrics is a leading international provider of life cycle management services for the power generation and electricity industries.

About Burloak Technologies

A leader in the additive manufacturing industry, Burloak Technologies provides engineering and design services for additive manufacturing, materials development, high precision CNC machining, post-processing and metrology. Burloak works with the most innovative companies in the space, aerospace, automotive and industrial markets to rapidly transition their most challenging part designs to be additively manufactured at scale. The Company is registered to AS9100D, ISO9001 and is Canada Controlled Goods Approved. For more information visit burloaktech.com.

About Samuel

Founded in 1855, Samuel, Son & Co., Limited, is a family-owned integrated network of metal manufacturing, processing and distribution divisions. Samuel employees provide metals, industrial products and related value-added services from locations across North America. The company leverages its industry expertise, breadth of experience and the passion of its people to help drive success for North American business – one customer at a time. For more information visit samuel.com.

About Kinectrics

Kinectrics is the category leader in providing life cycle management services for the electricity industry. Trusted by clients worldwide, our expertise in engineering, testing, inspection, and certification is backed by our independent laboratory and testing facilities, a diverse fleet of field inspection equipment and an award-winning team of over 1,000 engineers and technical experts. From initial design and type testing to operational deployment and maintenance services, Kinectrics collaborates closely with customers to ensure that utility assets perform safely, reliably and efficiently throughout their entire life-cycle. For more information visit kinectrics.com

For further information: Media Contact: Steve Snyder, Director of Marketing and Communications, Samuel, Son & Co., Limited, 289-442-3604, steve.snyder@samuel.com

ADVANCED MANUFACTURING ROADMAP FOR THE CANADIAN NUCLEAR INDUSTRY

A Potential Solution to Address CANDU Obsolescence Challenges and to Reduce Fabrication Costs of SMR Components

Prepared by:

KSB | OCNI | Kinectrics

December 14, 2021

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