Fabrication, Irradiation, and Testing of Zircaloy-2

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Outline

1. **Overview of Westinghouse AM efforts**
2. **Summary of 316L AM material evaluation**
3. **Production of Zircaloy-2 samples**
4. **Analysis of unirradiated material properties**
    - **Porosity/Density**
    - **O_2 content**
    - **Chemistry**
5. **Production of miniature tensile specimens**
6. **Irradiation in MIT test reactor**
7. **Planned analysis of irradiated material properties**

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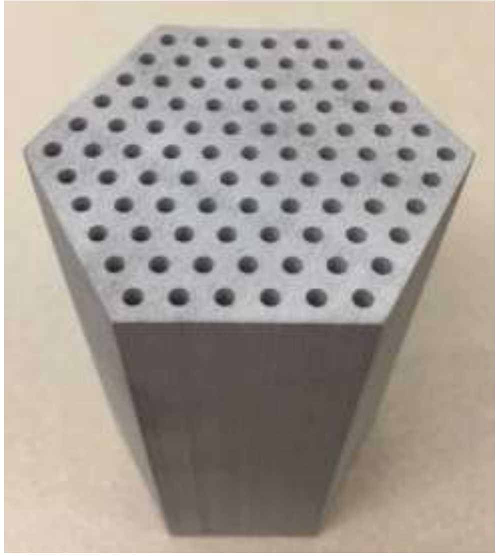
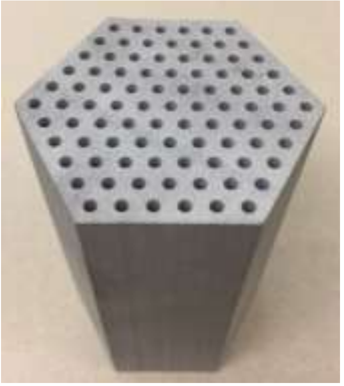
Overview of Westinghouse Additive Manufacturing Efforts

Outline

- Global Technology Development efforts
- Nuclear Fuel Components efforts
- Tooling and replacement parts
- Thimble Plugging Device (TPD) project



Global Technology Development Efforts (R&D)



OVERVIEW

- **Prototype components for SMR, advanced reactors and AM manufacturing/design demonstration**
- **Material development for next generation applications**
- **Support development of codes and standards (ASTM & ASME)**

BENEFITS

- **Design freedom: complex geometries, internal passageways, etc.**
- **Reduced design time: fast prototyping & mold production**
  - **Little to no tooling required**
  - **Design complexity at minimal cost**
- **Near net shape: reduced material, machining & welding**
- **Reduced lead-time / reduced supply chain**

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Potential Future Benefits to Nuclear Fuel

- Lower fuel assembly pressure drop
- Better flow mixing and greater heat transfer ability
- Less potential for leakers
- Greater accident tolerance
- Better fuel margins
- Extended fuel cycles

- Customizable fuel assemblies
- Less supply chain dependence
- Fewer overall suppliers
- Reduced time from concept to market
- Flexibility

Shatter Paradigms for Fuel Design Constraints Based on Traditional Materials and Manufacturing Limitations

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Additive Manufacturing and Nuclear Fuel

WEC Nuclear Fuel is pursuing the use of Additive Manufacturing (AM) in a variety of manners:

- **Design of advanced debris filtering bottom nozzle**
- **Advanced spacer grids optimized utilizing design freedom**
- **Evaluating available AM metal powders for use in fuel components**
- **Radiation exposure testing of 316L, Alloy 718, and Zr products**

Preliminary efforts to develop AM designs and alloys

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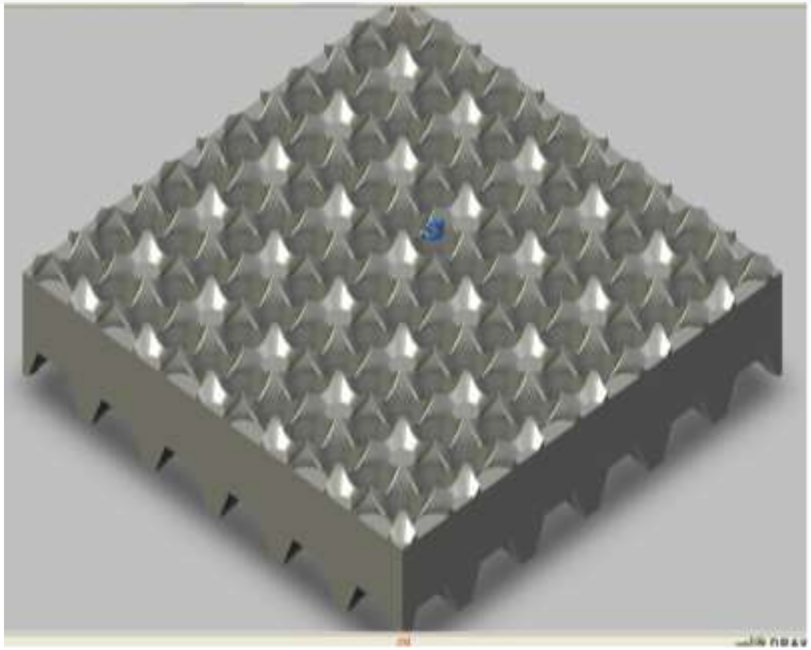
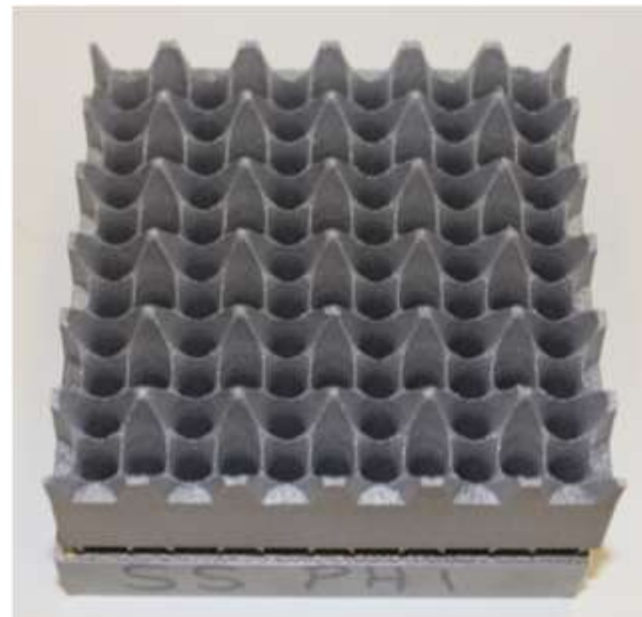
Advanced Debris Filtering Bottom Nozzle



- Additively manufactured and achieved a substantial pressure drop reduction



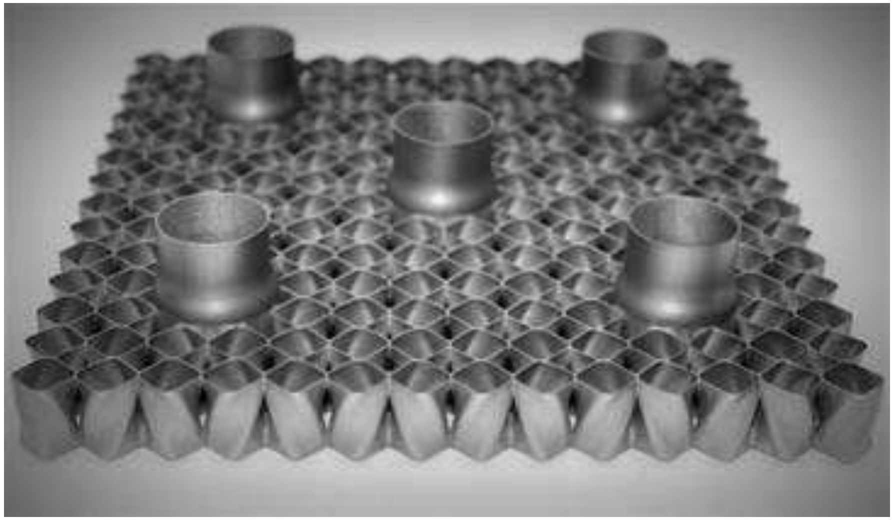
- This effort resulted in 24 unique plastic designs each tested in the “Vista” loop for hydraulic performance
- Used to quickly “optimize” designs for improved hydraulic performance

Prototyping to evaluate and optimize performance of concepts

Advanced Spacer Grids

Prototype grid printed using AM

- Grid (not printed) did not perform as expected in DNB testing
- Potential "fixes" could be realized using AM
- Possible opportunity to expand testing capabilities to enable prototype screening greatly reducing costs and improving development cycle times



Prototyping to improve results and shorten development cycle time

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Columbia Site Tooling Insert Application

Grid Tooling Inserts
(AM Tooling Application)

Blairsville Site Tooling Application

- **Original was five piece design with brass wear plate - heat treated to 36-44 Rc**
- **AM part printed in one build using tool steel – heat treated to 42 Rc**
- **Reduced need for replacement as the tool steel work hardens increasing useful life**

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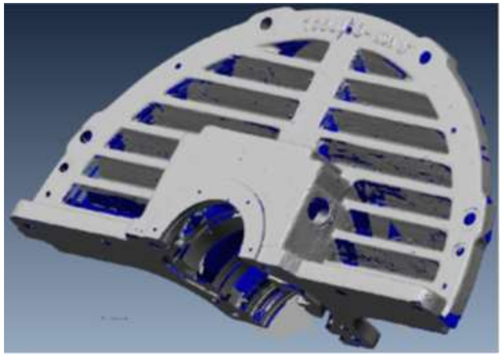
Replacement Parts Development Efforts

OVERVIEW

- **Demonstrating Reverse Engineering Process:**
  - **3D laser scanning → CAD Models → AM sand molds → traditional casting**
- **Multiple replacement castings have been identified**
  - **Difficult to procure replacement castings**



BENEFITS

- **AM complexity with traditional sand casting (☑ ASME/ASTM)**
- **Significantly reduced cost and lead-time**
- **Conversion to modern, digital design information and manufacturing**

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Replacement Parts Development Efforts

- **Worn out shaft repaired using plasma spray coating**
- **Nickel and molybdenum deposited onto the worn surfaces and part ground back into engineering specifications**
- **Able to return the part to service for about a third of the price of a replacement**

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TPD Project

- **Why the Thimble Plugging Device**
  - **<u>Low risk component for which consequences of failure minimal</u>**
  - **Fairly complex design promoting enhanced understanding of the AM design and building process**
  - **Constructed of material that has been previously tested in MIT reactor**
  - **Located in reactor region with fluence rate comparable to region of ADFBN placement in the core**
- **The AM TPD is intended to be produced for technology development and will not be produced in typical production QTYs**
- **AM TPD has not been redesigned to utilize AM benefits**

Improve our understanding of AM materials in radiation environment

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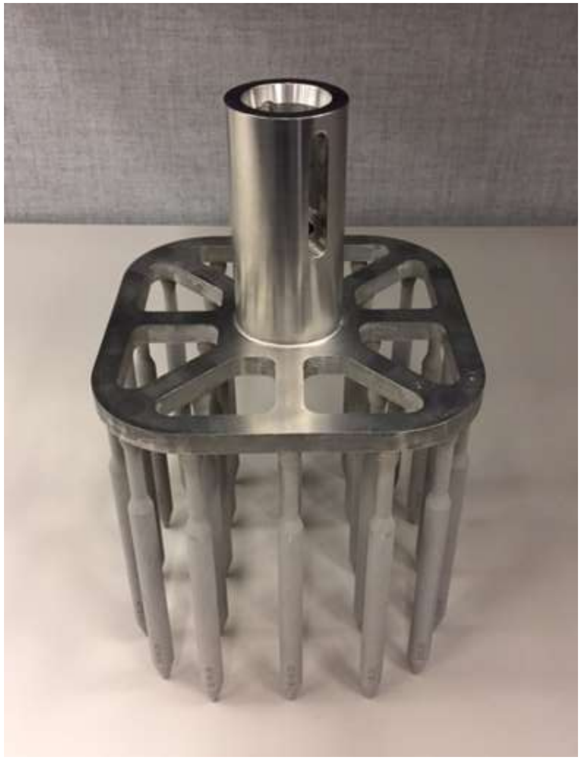
TPD Project

Current Status:

- **Prototype builds have been completed and proof of concept demonstrated**
- **Concepts and Issues meeting completed**
- **Design and Manufacturability meeting held**
- **Qualification Reports, CDI's, and PO's in place for production pieces**
- **Four qualification pieces have been built**
- **Testing of qualification pieces complete**



Non-Zircaloy AM Evaluations

Evaluating Commercially Available Materials

- **AM market has been growing dramatically the past several years**
- **Growth has been mainly driven by the medical and aerospace industries**
- **New material types and increased availability have been a result of this growth**
- **The <u>main</u> two alloys that are commercially available having potential crossover use in nuclear applications are Alloy 718 and Stainless Steel 316L**

Material availability is currently driven by non-nuclear applications

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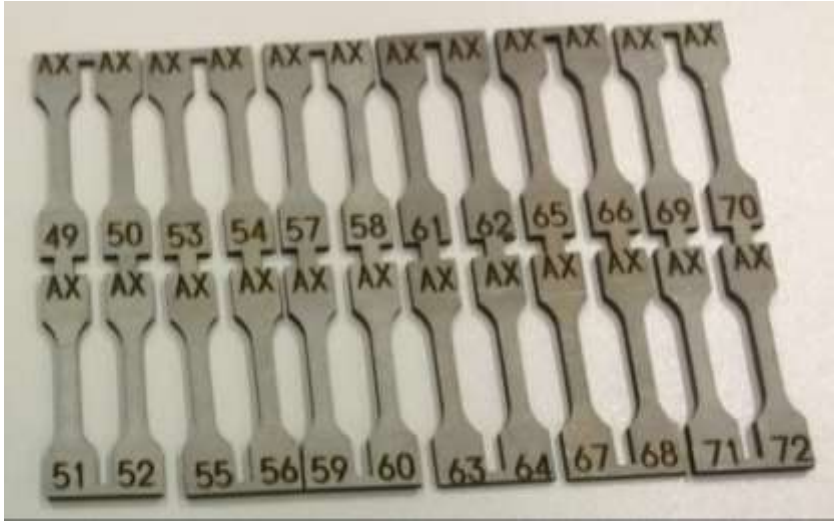
Radiation Exposure Testing of AM Materials

- **Currently, the nuclear industry does not have direct* radiation experience with AM materials**
- **To address this deficiency, WEC printed blocks of AM materials to produce mini tensile specimens**
- **316L and Alloy 718 specimens were placed in MIT's test reactor in October 2014 and were removed in May 2015**
- **Zr samples were placed in MIT's reactor in 2016, removed in 2016, and reinserted in 2017**
- **Samples have been evaluated by Westinghouse in hot cells at Churchill and tensile results were published in August 2017 (results are very promising)**

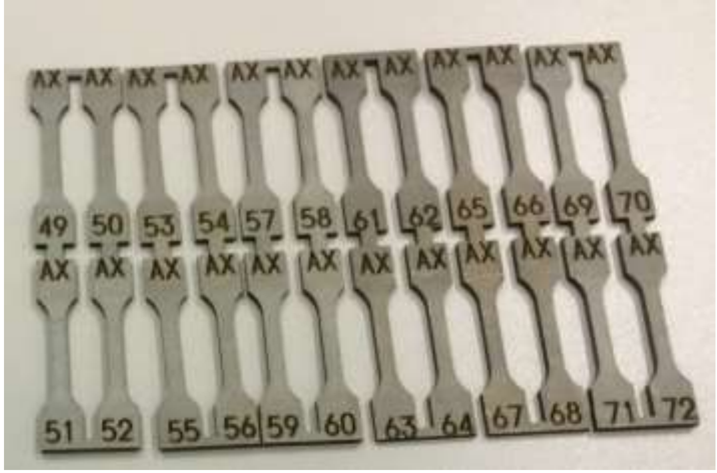


First of a kind radiation exposure

* The use of laser cladding for reactor internals could be considered a form of AM which has performed well.

Radiation Exposure Testing of AM Materials

- **This round of testing: compare the delta between before and after irradiation mechanical and microstructural properties**
- **Comparisons of the results to determine if the changes observed in AM materials are different than changes observed in cast or wrought materials when exposed to the same levels of radiation**
- **The absolute values obtained are not "in-scope" of this testing as they may be tailored through AM powder and process changes**



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Production of Zircaloy-2 Samples

Zircaloy-2 Effort Overview

1. **Procure and test Zircaloy-2 powder for DMLM machine – Two phased**
2. **Fabricate block of Zircaloy-2**
3. **Analysis of unirradiated material properties**
    - **Porosity/Density**
    - **O_2 content**
    - **Chemistry**
4. **Produce miniature tensile specimens**
5. **Irradiate in MIT test reactor**

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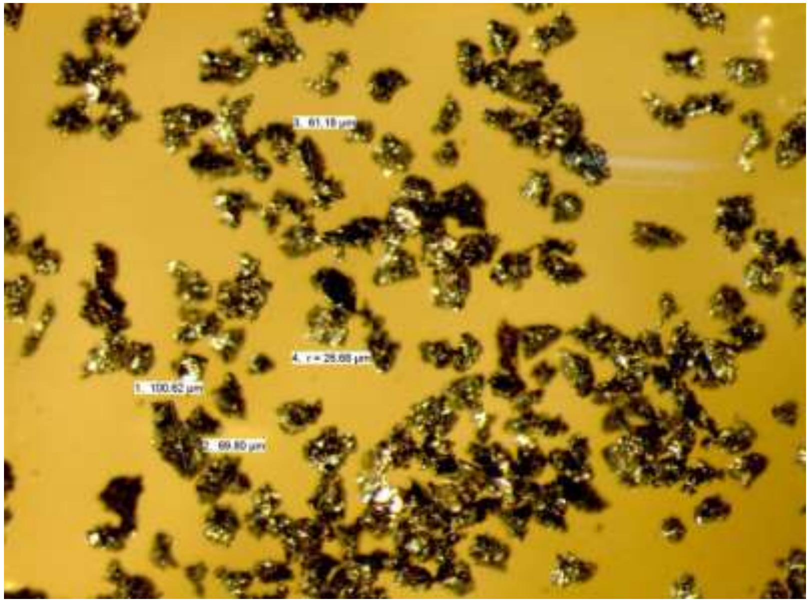
Zircaloy-2 Powder

1. **ATI Specialty Metals produced powder using hydride-dehydride method**
2. **Milled to make more spherical**
3. **Exposed to air slowly to "passivate" the powder for handling safety**
4. **Two efforts**



ATI Specialty Metals produced Zr-2 powder

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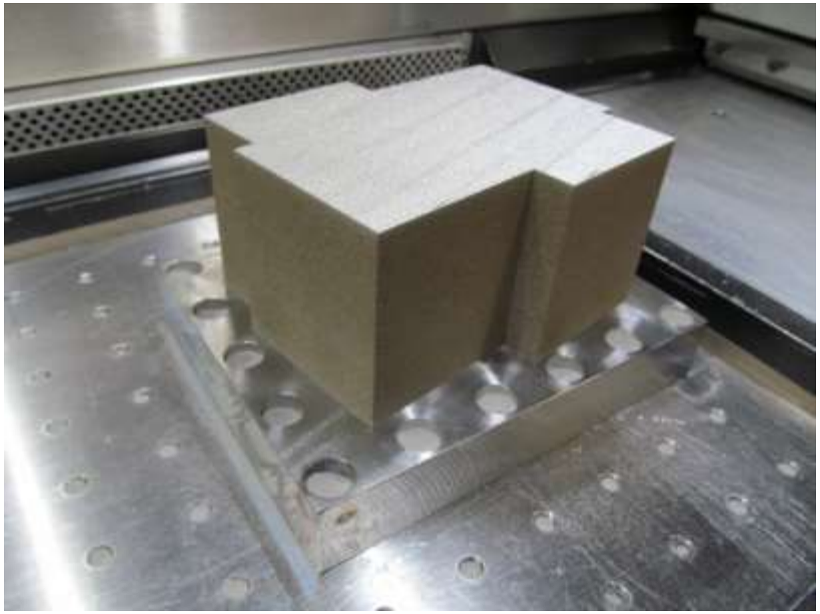
Feasibility Studies for Zirconium Based Powder

- **WEC procured a zirconium based powder for AM use**
- **Demonstrated that the AM process can be used to conglomerate zirconium based alloys**



Zirconium powder for AM under development

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Zircaloy-2 Powder

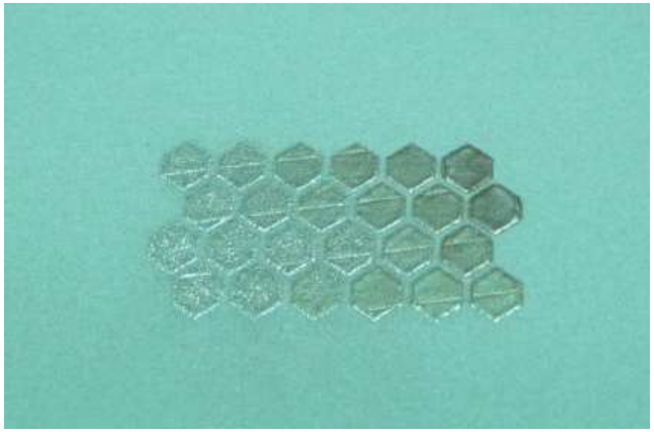
Particle sizes "typical" for laser powder bed process

Particle size [µm]	Wt %
< 25	0.3
25 – 38	7.8
38 – 45	15.8
45 – 53	32.8
53 – 63	34.2
63 – 75	8.9
> 75	0.2

ATI Specialty Metals produced Zr-2 powder

Fabricate Block of Zircaloy-2

1. **24 different parameters (travel speed and power) tested to determine “optimum’ settings**
2. **All settings utilized 40 micron layer thickness**
3. **Optimum settings determined by density measurements**



Parameter sets evaluated

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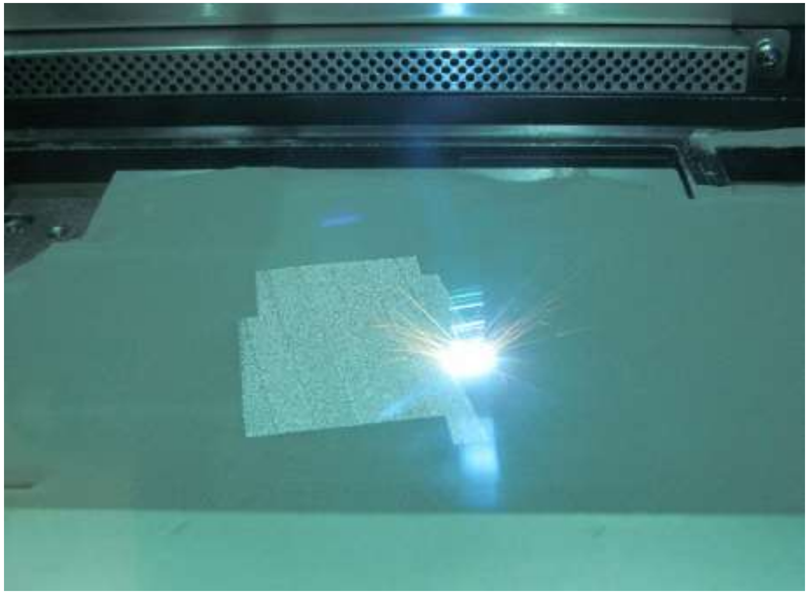
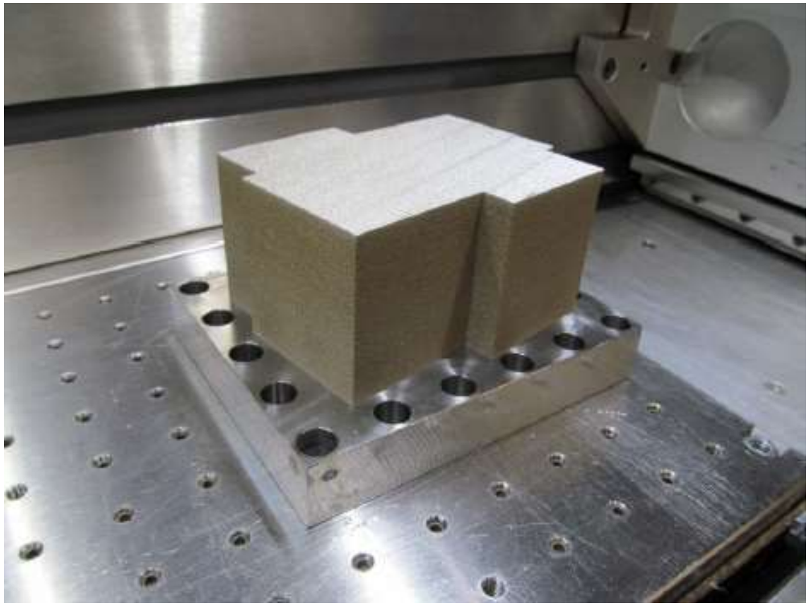
Fabricate Block of Zircaloy-2

Block shape optimized to maximize the number of tensile specimens produced





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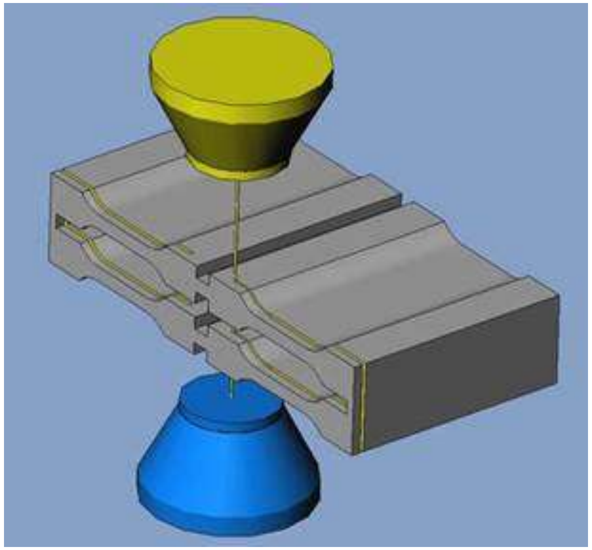
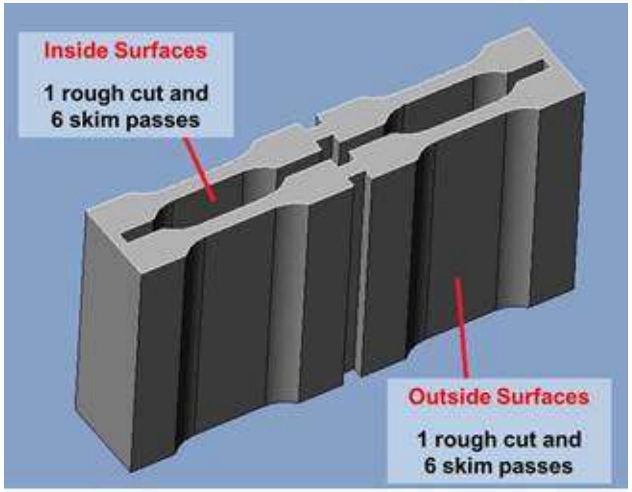
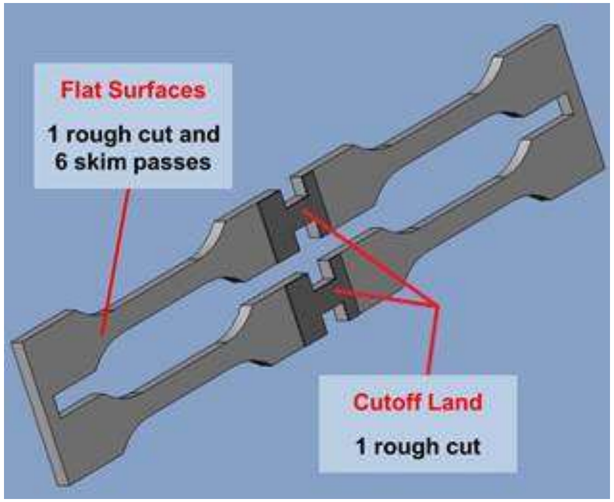
Produce Miniature Tensile Specimens

Tensile specimens wire EDM'd from Zircaloy-2 block

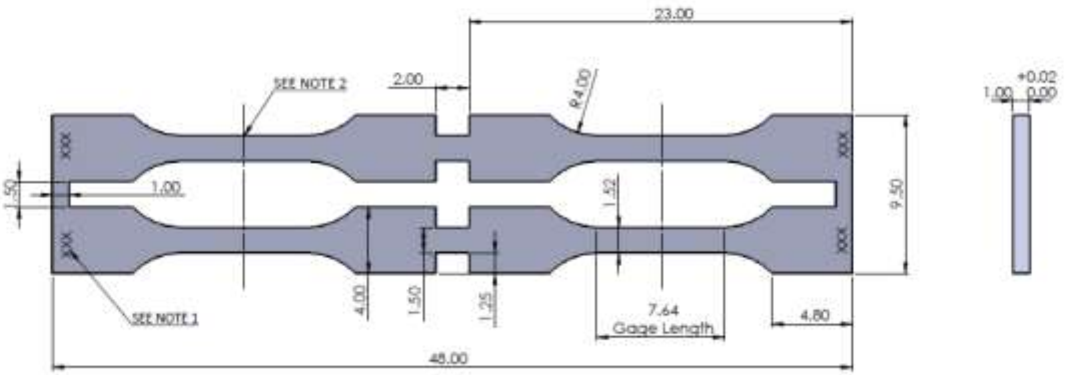


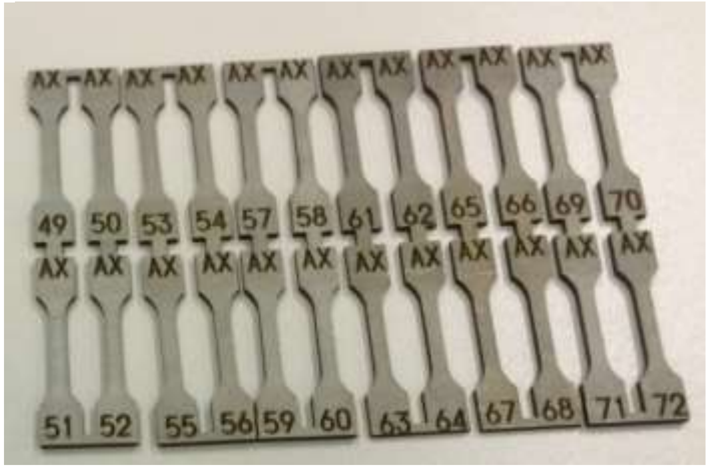




Produce Miniature Tensile Specimens

Laser etched with unique identification number





Unirradiated Material Analysis

- **Density evaluated**
  - Final density determined by ImageJ software
  - Density approximately 99.84%
  - Minimal LOF (lack of fusion) and no cracks
- **Metallography**
  - SEM performed
  - Consistent microstructure across samples
  - Finer grain structure near bottom of sample
  - Preliminary evaluation of suspected precipitate
- **Mechanical**
  - Needs to be performed

Final Chemistry

Element	UOM	Value
C	ppm	30
Cr	ppm	800
Fe	ppm	1230
H	ppm	36
Hf	ppm	26
Mg	ppm	1.6
N	ppm	120
Nb	ppm	< 50
Ni	ppm	500
O	ppm	1620
Sn	pct	1.35

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Irradiate in MIT Test Reactor

- Three tensile "quads" placed in test reactor in Dec 2015 and removed in June 2016
- Received approximately 0.7 to 1 dpa
- Three quads are currently stored at MIT
- Two quads to be reinserted and irradiated to ~ 2 and 3 dpa

Irradiated Zr-2 specimens ready for analysis

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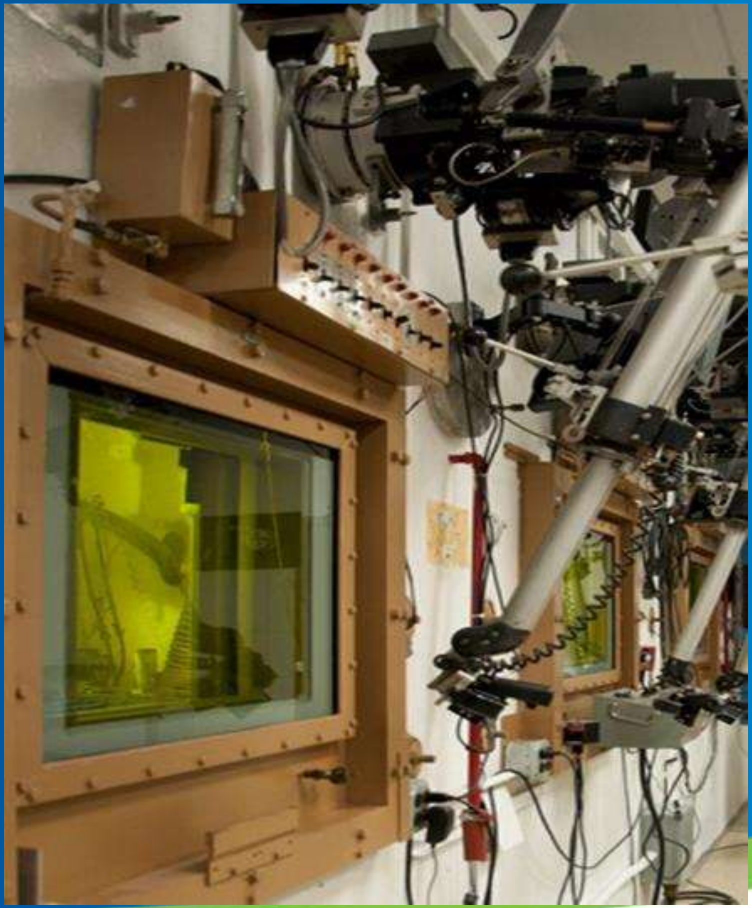
NSUF DOE Sponsored Project for Testing and Evaluation of AM Zircaloy-2



FY2017 DOE Office of Nuclear Energy Consolidated Innovative Nuclear Research (CINR) Funding Opportunity Announcement (FOA) DE-FOA-0001515

Awarded Proposal: "Radiation Effects on Zirconium Alloys Produced by Powder Bed Fusion Additive Manufacturing Processes, NSUF-2: Nuclear Science User Facilities Access Only"

- Scope of work includes unirradiated zircaloy-2 and irradiated zircaloy-2 (1, 2 and 3 dpa samples)
- Notified of award June 14, 2017
- Samples are currently at MIT
- Total award value ~ $830,000
- Three year contract

Westinghouse Churchill is a DOE NSUF partner laboratory – the only commercial laboratory partner

Program Schedule

Task Number	Comment or Material Under Evaluation	Calendar Year 2017				Calendar Year 2018				Calendar Year 2019				Calendar Year 2020			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1-16	1 dpa Irradiated AM Zr Quad				x	x	x										
17-26	Unirradiated AM Zr Quad					x	x										
27-36	Unirradiated Conventional Zr Quad					x	x										
37-38	Data Analysis and Reporting							x									
39-53	2 dpa Irradiated AM Zr Quad					x	x	x									
54-55	Data Analysis and Reporting								x								
56-71	3 dpa Irradiated AM Zr Quad									x	x	x					
72-84	3 dpa Irradiated Conventional Zr Quad									x	x	x					
85-86	Data Analysis and Reporting												x				
87-88	Final Cleanup and Project Close Out													x			

Scope of Work

- **Provide radioactive shipping container and arrange/coordinate 3 radioactive shipments from MIT to Westinghouse Churchill (1, 2 and 3 dpa samples)**
- **Visual inspection and photography**
- **Miniature tensile tests (room and elevated temperature)**
- **Fractography**
- **Bulk hydrogen analysis**
- **Light optical microscopy**
- **Scanning electron microscopy, including EBSD**
- **Microhardness**
- **TEM originally included in scope of work but was subsequently removed to reduce program cost**

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Notes

- **Zircaloy-2 sample fabrication and irradiation previously performed under Westinghouse funding**
- **DOE NSUF is funding PIE work only (and complimentary unirradiated sample evaluations)**
- **Work to begin late 2017 or early 2018 – contract received and being reviewed and approved by Westinghouse contract/legal personnel**