LOCKHEED MARTIN

QuadCity Manufacturing Lab

DOE Nuclear Energy Enabling Technologies (NEET) AMM

Direct Manufacturing of Nuclear Power Components

September 29th, 2015

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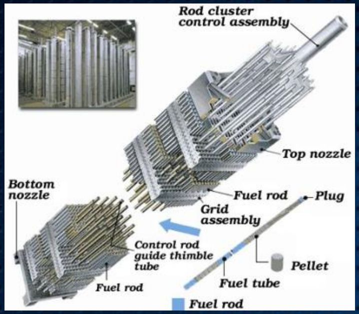
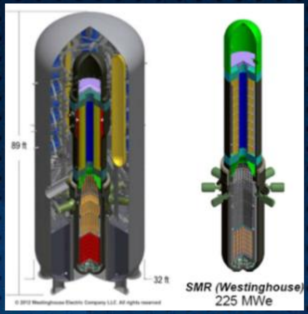
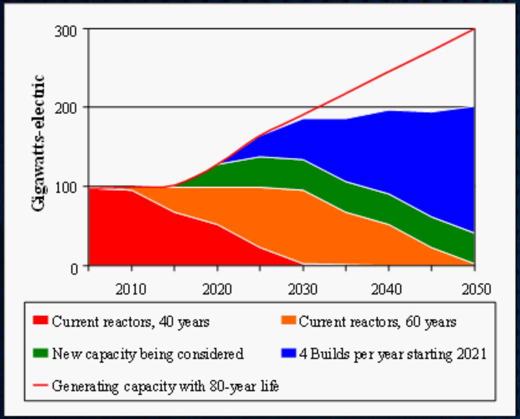
NEET Program Introduction

- Purpose:
  - Support U.S. development to thrive in $B international market for nuclear power additive technologies that significantly reduce development and operational costs and manufacturing lead time for nuclear Rx components
- Objectives:
  - Develop baseline and advanced rad tolerant alloys
    - Investigate nanophase modification
    - Identifying reduced life cycle costs
  - Demonstrate cost and schedule reduction using additive methods.
- Approach:
  - Build manufacturing demonstrations of complex parts demonstrating design flexibility and shortened design-to-manufacturing cycles
  - Employ nanophase alloy modification via Laser Direct Manufacturing (LDM) to create enhanced rad tolerant components
  - Explore cost and schedule benefits through case study and business case analysis







Advanced/Affordable Manufacturing Methods are Key Enablers for competing in $700B global market

Overview

- Materials selection
- Fabrication and characterization of alloy samples – Nanoscale modification
- ODS SS Development
- Demo Fabrication
- Manufacturing Study
- Path Forward

	Inconel 600	Inconel 718	Inconel 800	316L SS	ODS 316L SS
LDM Trials	Complete	Complete	Complete	Complete	Complete
Microstructures	Complete	N/C	N/C	Complete	Complete
Mechanical Properties	Complete	N/C	N/C	Complete	N/C
Test Specimens	Complete	Complete	Complete	Complete	Complete
Demo Articles	Complete (3x3*, 10x10 and 15x15)	Complete (3x3*)	Complete (3x3*)	Complete (3x3)	N/A

**** Baseline 3x3 and thin wall demo samples***

Baseline & Alternative Alloys

Comparison criteria for selection of alternative nuclear materials

Comparison criteria

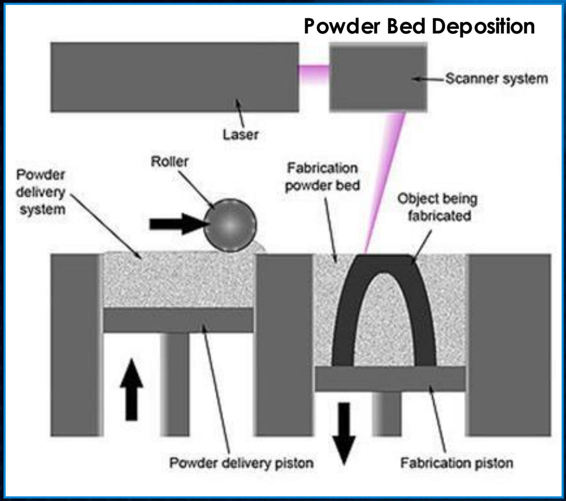
- Low neutron absorption
- Elevated temperature mechanical properties
  - Creep resistance
  - Long-term stability
  - Compatibility with reactor coolant
- Resistance to irradiation-induced damage (greater than 200 dpa)
  - Radiation hardening and embrittlement
  - Void swelling
  - Creep
  - Helium-induced embrittlement
  - Phase instabilities

Alternate Nuclear Materials

- BASELINE: Traditional ferritic/martensitic steels (HT-9) or later generations of F/M steels
- OPTION 1: ODS steels to examine effect of direct manufacturing methods on nanoscale oxide domains
- OPTION 2: Inconel 800 series of materials to study the effect of processing parameters offered by direct manufacturing methods to improve performance under irradiation
- OPTION 3: Among the refractory alloys, the Mo (TZM) alloys. These have a high operating temperature window and also, the most information on irradiated material properties

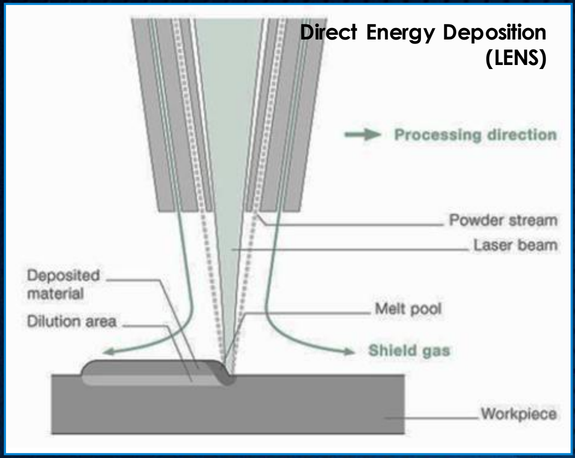
Based on customer discussions, materials down-selected to 316L SS, Inconel alloys and ODS steels

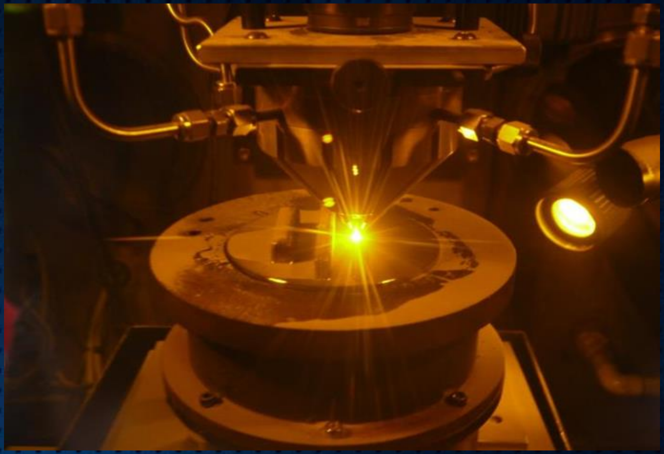
Metal AM Technologies – Powder Bed Fusion and Beam Deposition



Applications
- Functional prototype parts
- Legacy parts
- Parts with complex geometries
- Small production runs

Equipment at QCML
- EOSINT M270 Extended-Ti
- Build Vol: 9.85" x 9.85" x 8.5"





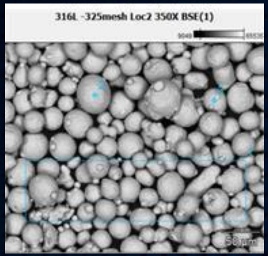
Applications
- Laser Cladding
- Part fabrication
- Adding features to parts
- Part repair

- Equipment at QCML
  - Customized 4-axis Cell
    - 48" h x 20" w x 20" d x 360° roll
  - Customized 3-axis Cell
    - 12" x 12" x 10"

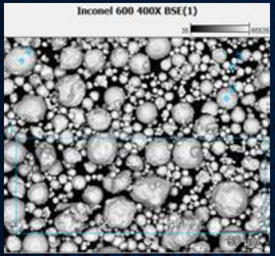
Powder bed and Beam deposition methods were both utilized in samples processing

Approach to Samples Development

- Method of Fabrication
  - Powder bed dep. process
    - 316L SS, Inconel alloys (600, 718, 800)
  - Beam deposition method
    - ODS – 316L SS
- Availability of powders
  - Particle size
  - Specification
- Parameter optimization for QCML Electro Optical System (EOS)
  - Alternative alloys
  - Scan speed
  - Laser power



316L SS -325 mesh

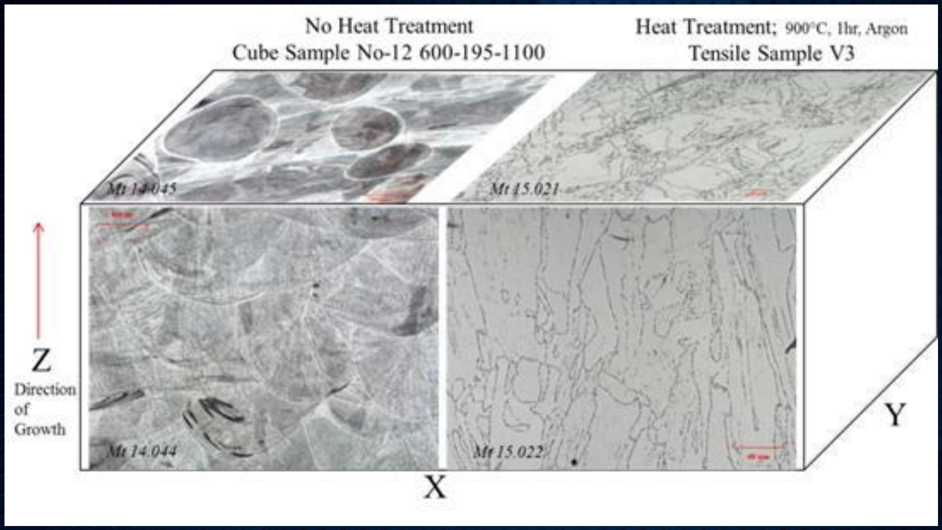


Inconel 600

	Inconel 600	Inconel 718	Incoloy 800
Chemical composition (%)	72 **Ni**, 14-17 **Cr**, 6-10 **Fe**, 0.15 max **C**, 1 max **Mn**, 0.015 **S**, 0.50 **Si**, 0.50 **Cu**	50-55 **Ni**, 17-21 **Cr**, 11-22.5 **Fe**, 0.08 max **C**, 0.35 **Mn**, 0.015 **S**, 0.35 **Si**, 0.3 **Cu**, 0.2-0.5 **Al**, 0.65-1.15 **Ti**, 0.015 **P**, 1 **Co**, 4.75-5.5 **Nb**, 0.006 **B**, 2.8-3.3 **Mo**	30-35 **Ni**, 19-23 **Cr**, 39.5 min **Fe**, 0.1 max **C**, 0.8 max **MN**, 0.008 max **Si**, 0.4 **Cu**, 0.15-0.60 **Al**, 0.15-0.60 **Ti**,
Melting point (F)	2470-2575° F	2300-2435°F	2471-2525°F
Density (g/cm³)	8.47	8.19	7.94
Crystal structure*	FCC	FCC	BCC or FCC
Process parameter study conditions: Power (W)	150 - 195	150 - 195	150 - 195
Process parameter study conditions: Scan Speed (mm/s) in increments of 100	800-1400	800-1400	800-1400
Density (g/cm³) data range results:	8.29-8.39	8.11-8.20	7.80-7.91
Test coupon build conditions:	195 W, 1100 mm/s	195W, 1200mm/s	195W, 1200mm/s

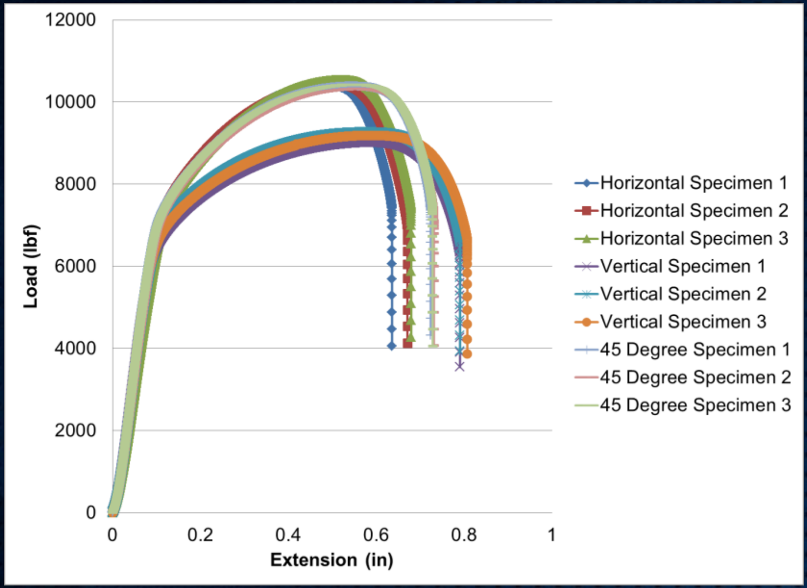
Inconel 600 Results

Microstructure Inspection



Etched Inconel 600 non heat treated vs. heat treated

Mechanical Performance

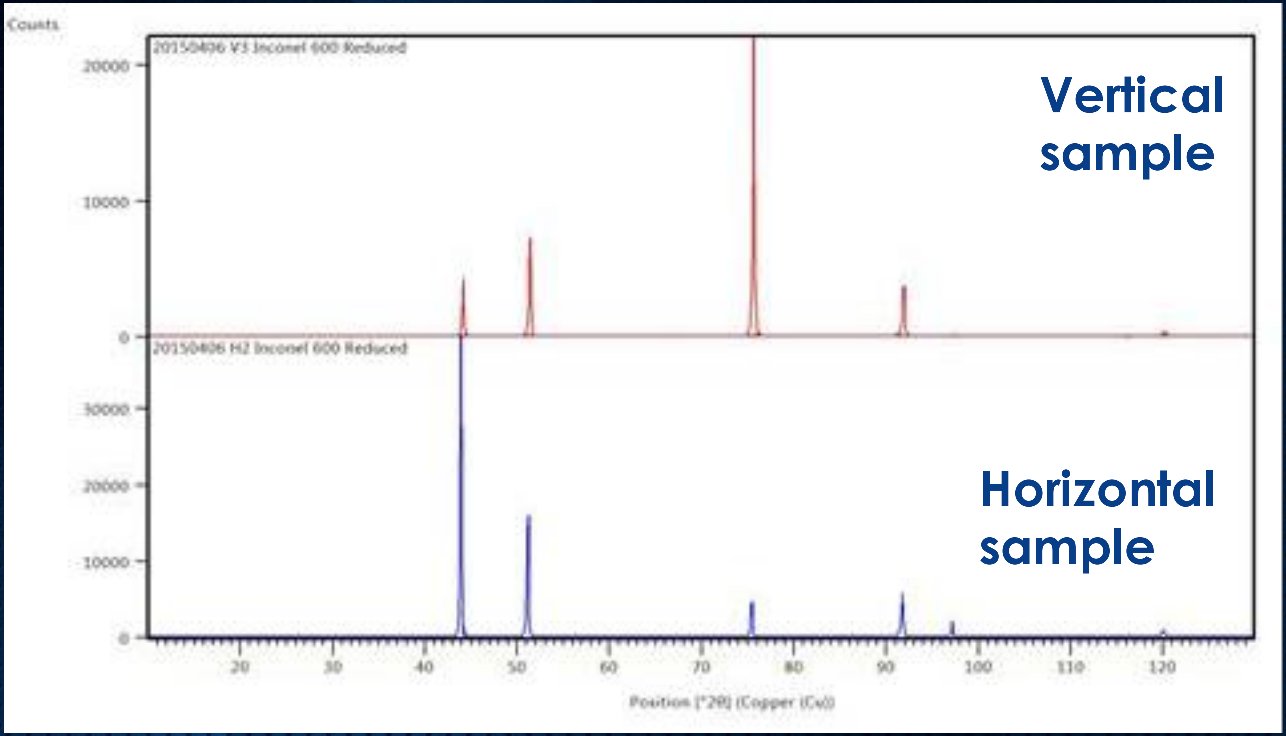


Inconel 600 horizontal, vertical and 45° specimen mechanical testing

The directionality of manufacture has impact on the grain structure and the maximum tensile strength

XRD data on Inconel 600 AM samples

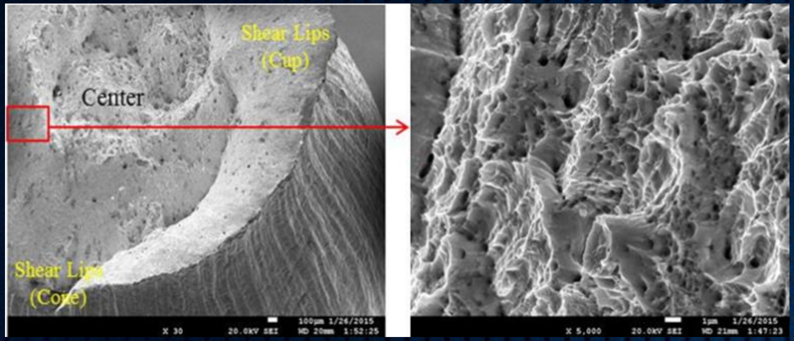
- XRD data shows the differences in peak ratios between the horizontally and vertically built specimens

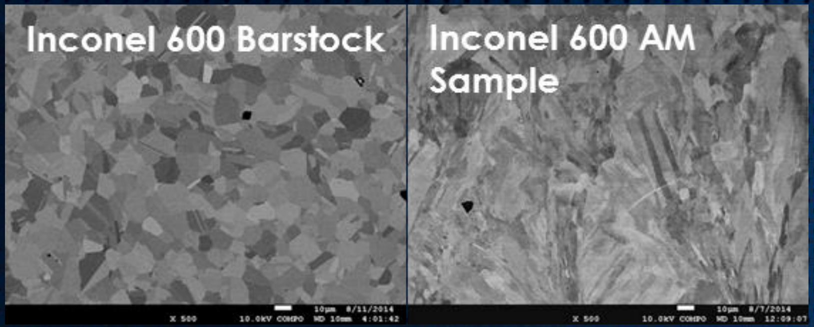


- Data supports directional solidification texturing seen in the micrographs

Summary of Sample Fabrication and Characterization

- Mechanical testing of AM samples shows directional dependence
- Optical micrographs show the laser solidification patterns for both planes
- Fracture surface analysis showed ductile cup-and-cone fracture
- Tensile and hardness properties comparable to bar stock
- XRD data supports observation of preferential grain growth
- Microstructure control possible by varying process parameters

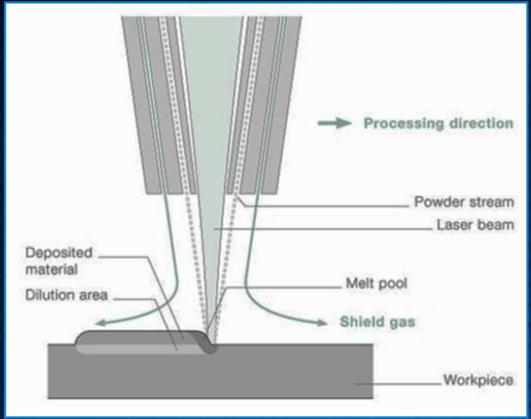




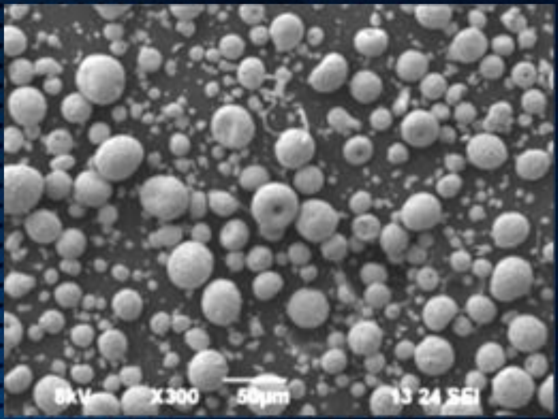
316L SS and Inconel alloys demonstrated bar stock performance w/ potential for designing to preferential directionality

Experimental Alloy – ODS 316L-SS

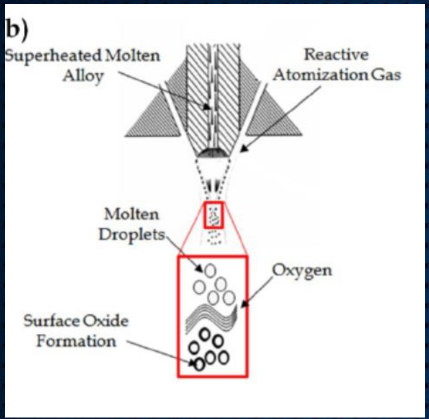
- Introduction of stable nanoscale phases of carbides, nitrides and oxides is method of obtaining high-temp strength
- Oxide Dispersed Strengthened (ODS) steels to examine effect of direct manufacturing methods on nanoscale oxide domains
- ODS powders not readily available
- Three methods explored to make the ODS steel powders:
  - Spray drying technique – Flurry Powders
  - Gas atomization reaction synthesis – Ames Laboratory (Anderson)
  - Mechanical Ball milling



LENS Beam Dep Process



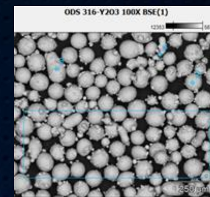
Spray Drying Formulation (Flurry)



Gas Atomization (Ames)

ODS Trials / Samples / Summary

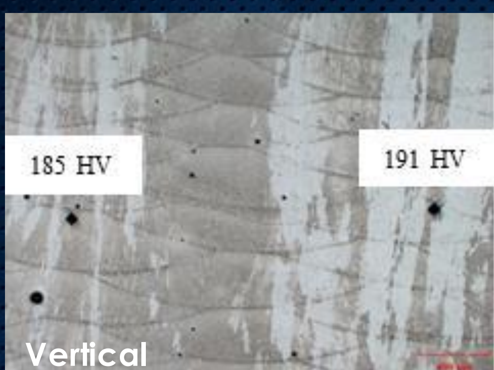
- Ball milling technique successful in creating ODS powder
- Developed process based on best initial parameters – process not optimized
- Microstructure showed rapid solidification
- Yttria identified in EDS sample data
- Laser melt pools visible
- Hardness data (one sample only) correlates to the hardness to 316L SS
- HIP samples – to be tested and examined



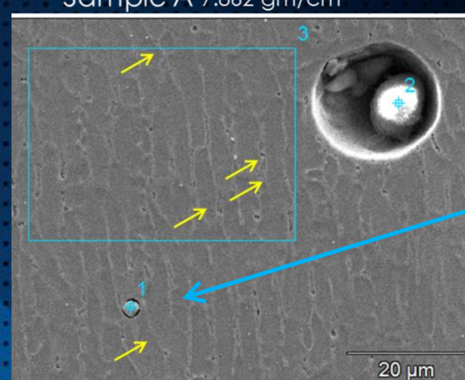
	O	Si	S	Cr	Mn	Fe	Ni	Y	Mo
ODS 316-Y2O3 pt1	5.0	0.6	0.3	16.0	1.8	59.2	8.9	7.3	0.9
ODS 316-Y2O3 pt2	4.5	0.6	0.2	15.3	1.6	60.4	9.8	6.5	1.2
ODS 316-Y2O3 pt3	4.3	0.7	0.0	15.1	1.2	64.8	10.1	2.3	1.6
ODS 316-Y2O3 pt4	1.4	0.2	0.0	16.5	2.4	66.4	7.5	5.2	0.4
No Spec for ODS									

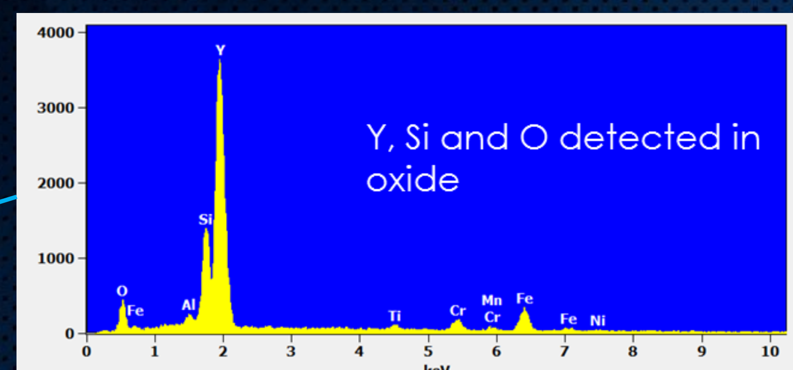
ODS Powder Formulation

Process Development Trials



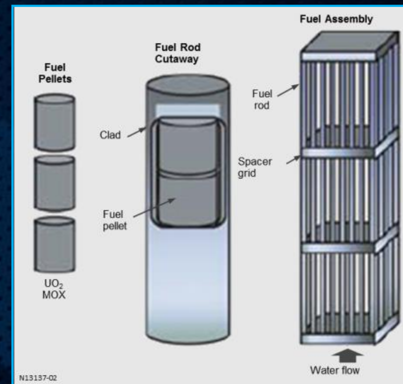
Sample A 7.862 gm/cm³

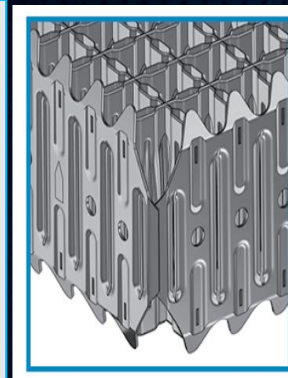


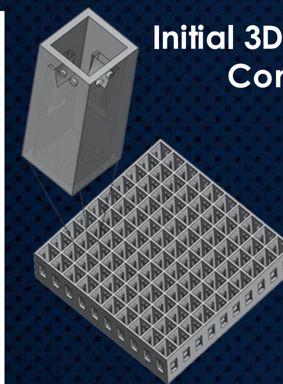


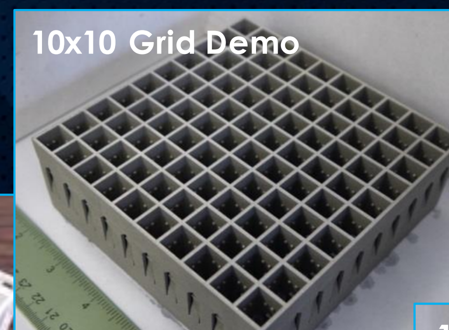
Demonstration Approach/Builds

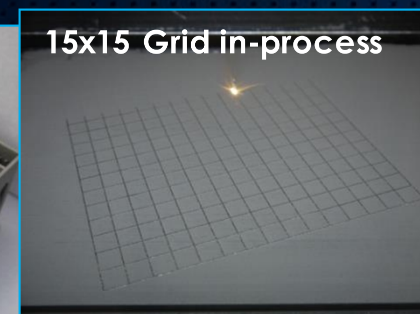
- Defined reactor component
- Developed notional design based on literature
- Explored collaborations to obtain actual CAD drawing
- Rapid prototyping
- Fabrication based on material process development
- Dimensional study






Initial 3D CAD Concept


10x10 Grid Demo


15x15 Grid in-process


Actual 8x8 Spacer Grid


Prototype

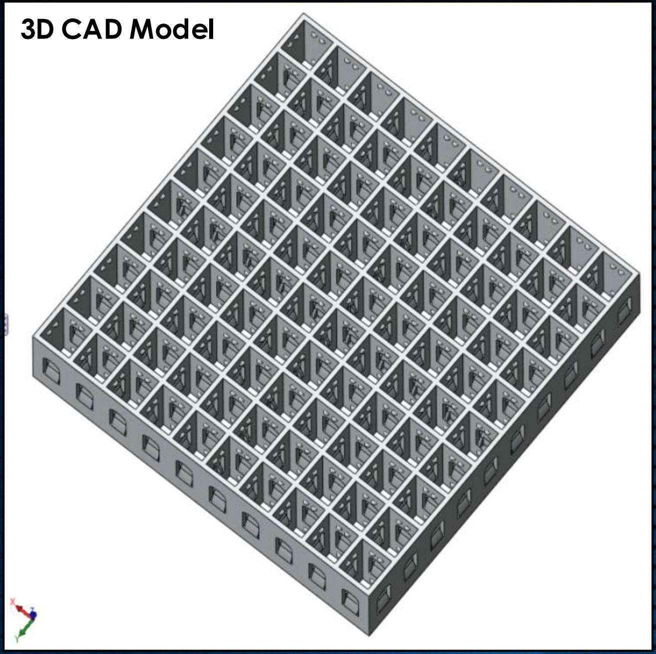

Wall Thickness Study

15x15 Thin wall Demo

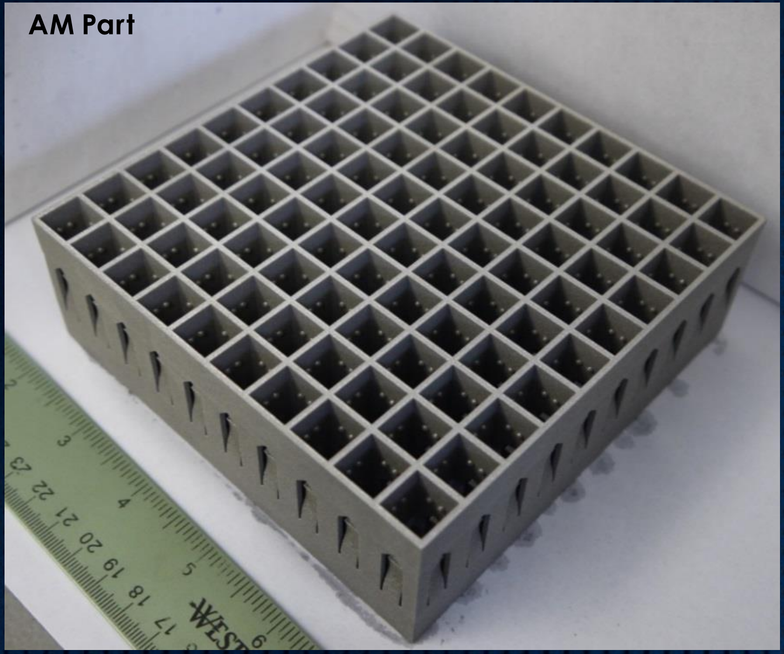
Case Study – AM Part Fabrication

- A simple 10x10 spacer grid design was developed w/ integral springs and rod positioning dimples
  - 5.19in x 5.19in x 1.75in
- Grid was fabricated out of Inconel 600 using a EOSINT M270 powder bed fusion tool at QCML in Rock Island, IL

CAD model



AM Part



Major Cost Elements by Fabrication Method

	Cost Element	Category	Traditional Manufacture	Cost Estimate	Additive Manufacture	Cost Estimate	Comments
1	Design and Analysis	Labor	Grid design, FE modeling for analysis, assembly fixture design, programming/teaching laser welding robot.	(# hrs) x ($__/hr labor rate)	Grid design, FE modeling for analysis, preparing part file for AM tool (scale for CTE shrink, add supports).	(# hrs) x ($__/hr labor rate)	Design is optimized for each fabrication method
2	Raw Materials	Materials	Inconel bar/plate stock	unknown	Inconel alloy powder	(part vol)x(density)x($__/lb metal powder)	
3	Pre Machining	Labor	Initial machining of subcomponents prior to welding into grid assembly	(# hrs) x ($__/hr labor rate)	N/A	N/A	No pre machining for AM part
4	Set-Up	Labor	Set-up or assembly of sub pieces into grid using fixtures	(# hrs) x ($__/hr labor rate)	Prepare AM tool (set-up platen, load powder, purge, etc.)	(# hrs) x ($__/hr labor rate)	Traditional method is skilled labor intensive
5	Hardware Run	Capital, Facilities, Labor	Laser welding system cost, power usage, purge gas usage, other consumables cost, maint/service contract, etc.	(# hrs run time) x ($__/hr)	AM system cost, power usage, purge gas usage, other consumables cost, maint/service contract, etc.	(# hrs) x ($__/hr rate)	Data available for AM from QCML
6	Post Processing	Capital, Facilities, Labor	Post weld heat treat for stress relaxation	(# hrs) x ($__/hr rate)	HIP and/or heat treat	(# hrs) x ($__/hr rate)	
7	Post Machining	Labor	N/A	N/A	Post machine to remove from platen and clean-up critical locations as needed.	(# hrs) x ($__/hr labor rate)	Probably not required for traditional part
8	Quality Check	Labor	Post fabrication qualification of part (dimensional accuracy check)	(# hrs) x ($__/hr labor rate)	Post fabrication qualification of part (dimensional accuracy check)	(# hrs) x ($__/hr labor rate)	Assume same for both
9	Scrap Loss	Materials	Scrap loss	unknown	Scrap loss	unknown	Assume same for both

- Low volume fabrication estimate of 10 x 10 Inconel grid ~ $6300
- Fabrication time on the order of days
- Would constitute ~ 40 to 50% of total refueling fabrication costs at this price
- Value comes in schedule savings, strategic build capabilities and enabling of new designs and improved performance.

Manufacturing Study Summary

- Manufacturing
  - Fabrication cost elements
  - Direct comparisons are challenging
  - Analysis suggests cost savings may not be readily attainable except for specific cases
  - Strategic value as driver for additive manufacturing
- Path Forward
  - Develop a more comprehensive understanding of the component design and parts
  - Identify areas where additive manufacturing enables new capabilities and designs
    - Obsolete parts
    - New designs not attainable through traditional manufacturing
    - Enabled performance (e.g., ODS SS)
  - Develop mature cost capture models and business cases

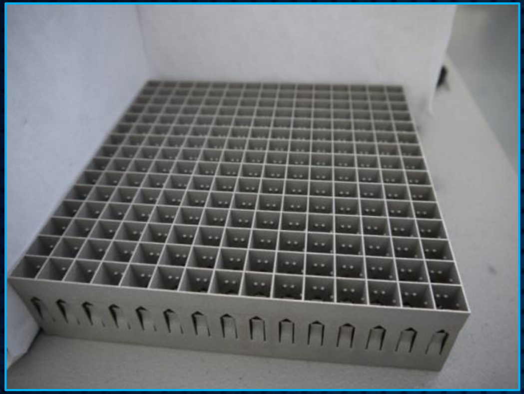
Path Forward

- Continued development on alloys
  - Design impact of directional performance
  - Powder formulation
  - ODS process development
- Radiation testing
  - Nominal alloys
  - Novel nano-tailored alloys
- Business case development

- NEET Sample Testing w/ Texas A&M
  - Approval from DOE to use samples for testing
  - Low dpa in-core testing and high dpa accelerator testing of X/Y/45° build directions

Summary

- Completed manufacturing demonstrations of notional fuel bundle spacer grid
- Demonstrated design flexibility (size and thickness) and shortened design-to-manufacturing cycles
- Demonstrated directionally dependent structure variation and performance via LDM for enhanced rad tolerant components – Inconel and ODS alloys
- Investigated cost and schedule benefits of spacer grid manufacturing cycle



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