Potential for Additive Manufacture in Nuclear Thermal Propulsion (NTP)

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Background

- NTP is under investigation to enable rapid-transit of human missions beyond low earth orbit.

- Rocket engine manufacturers faces significant challenges:
  - High complexity
  - Low production rate
  - Stringent requirements while under extreme operational conditions
  - High cost

- Leverage additive manufacture (AM) to decrease lead time and cost of rocket engines.
  - NASA, SpaceX, Aerojet-Rocketdyne, Blue Origin, and others are engaged in AM development.


Additive Manufacture Demonstration Engine (AMDE) Test at MSFC

Objectives

- Provide a general overview of AM.
  - Advantages & Disadvantages.
  - Process and utilization.
  - Engine specific considerations.
  - Evaluation for use in NTP.
  - Identify components, materials, and processes to aid NTP.

- Additive Manufacture: "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining."
  - ASTM standard F2792-10
  - https://www.youtube.com/watch?v=loSXlkrmzyw

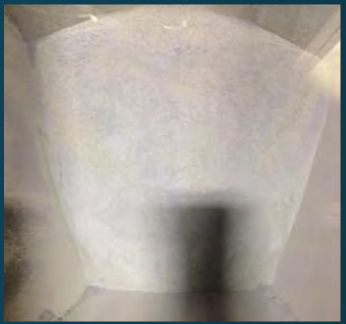
- AM complements traditional powder metallurgy and machining.
  - Traditional manufacturing is still required.

Advantages

- Advantages:
  - Increased design freedom and customization.
  - Net shape parts.
  - Light weight "lattice" structures via topology optimization.
  - Complex internal channels.
  - Part count reduction (reduces braze and weld steps) .
  - No additional tooling required.
  - Relatively short production time.
  - Residual porosity: >99.5% TD possible.
  - Properties: better than cast, below wrought.
- Apply AM to high complexity, low production rate components.
  - Supplement traditional manufacturing.
  - AM applied to low complexity and high production rate components will cost substantially more when compared to traditional manufacturing and production rates will take longer.
- Produce complex geometries in a short time compared to traditional methods.
- High hourly rates offset by reducing labor costs to produce complex components.

Disadvantages

- Misconceptions
  - *NOT* cheaper than traditional manufacturing on an hourly basis.
  - Produces significant waste: spent powder, build plates, failed builds.
  - Require substantial touch labor.



Spent build plates and oversized powder

- Disadvantages:
  - Materials must be weldable for PFB.
  - Metal build envelope size limit: 800 x 400 x 500 mm.
  - Long build time = low production rate.
  - Design constraints (no overhangs > 45°, minimum hole size, etc).
  - Non-ideal microstructure and surface roughness require HIP and surface modification.

- Property Variability.
  - Properties dependent on starting powders, process parameters, and post-processing.
  - Anisotropic properties in the build direction (Z).
  - Size: small-scale vs. full-scale builds.
  - Build volume spatial location.

- Flight certification and qualification: add 30% cost vs. traditional manufacturing.

AM Process

DESIGN & ANALYSIS

- Performance Requirements

-Design intent, design for AM, GD&T

-Export .stl

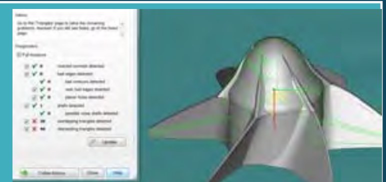
BUILD PREPARATION

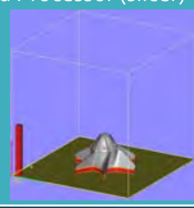
-Repair .stl

- Build Orientation

- Support Generation

- Build Processor (slicer)





BUILD

- Layer monitoring

- Virtual part model (3D flaw mapping)

- Compare virtual to LMC model

- Predict microstructure, flaw distribution, properties , geometry

POST-PROCESS

- Stress Relieve

- Plate Separation

- HIP

- Anneal

- Machining

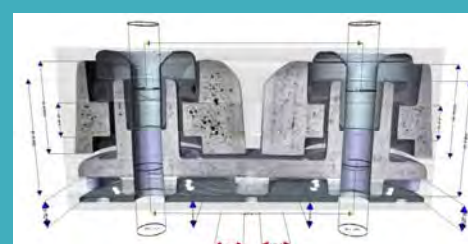
- Surface Roughness Modification : shot peen, extrude hone, etc

-Mechanical Testing

FLIGHT QUALIFICATION & ACCEPTANCE

- X-ray CT

- Neutron CT



IMPLEMENTATION

- Testing / Flight

- Post-ops Inspection

- NDE / Destructive evaluation

Rocket Engine Specific AM Factors

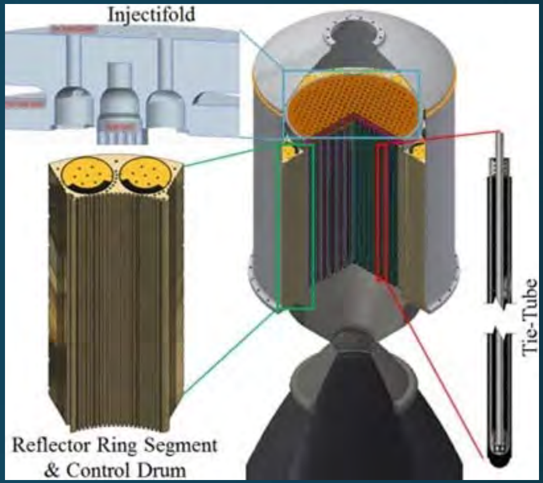
- Low factors of safety compared to other industries.
  - Human rating requires FS>1.2.
- Surface finish modification.
  - Impact of near-surface porosity high cycle fatigue (HCF) knock down factors.
  - Slurry or extrude hone.
  - Machining.
- Application dependent powder.
  - Gas atomized process: non-rotating components.
  - Rotating electrode process: rotating components.
  - Powder size distribution.
  - Powder density.
  - Contaminant limits.

Demonstrated Materials of Interest

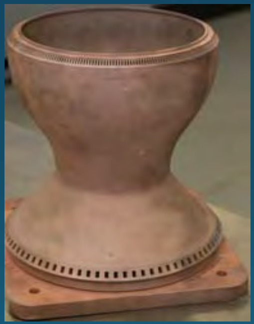
Inconel 625	CM 247	AlSi10Mg
Inconel 718	CoCr	GRCop-84
Rene N5	316L SS	Ti
Hastelloy-X	Marginal steels	Ti6Al4V
Hanes 230	Ceramics	TiAl

Applying AM to NTP

- From 2013-2015 a technically detailed NTP engine system and component design study was conducted (e.g. SCCTE).
- Component manufacture process evaluated.
- Identified NTP components potentially produced through AM:
  - Superalloy turbopump turbine, impeller, housing
  - Regnerative cooled nozzle (liner & jacket)
  - ZrC tie-tube sleeve insulators & slats
  - AlBeMet 162 Injectifold
  - B_4C neutron shields
  - Lines, ducts, valves
  - Pogo baffle & accumulator
  - Potentially others
- Prototype demonstration.
  - Fabrication (plastic to metal).
  - Testing (separate effects to combined effects).
  - Iterate.



Notional NTP core components

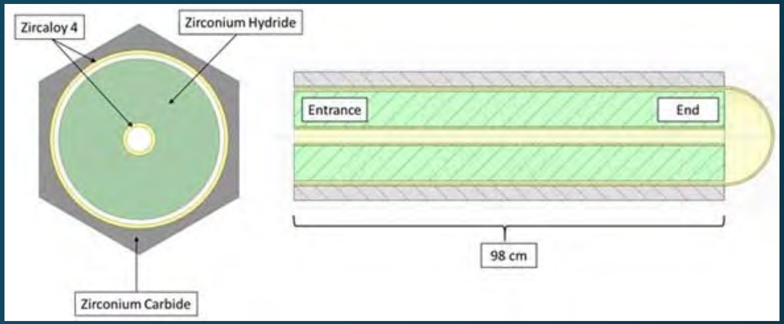

GRCop-84 regen nozzle liner


Injector and pogo baffle


Injectifold section demo (sterolithography)

Development Example

- ZrC tie-tube sleeve insulators & slats:
  - 60 %TD required to act as an insulator.
  - Net shape.
- B_4C neutron shield elements (internal shield):
  - Net shape.
  - Actively cooled by propellant.
  - Flow passages or porosity.
- ExONE M-Flex:
  - Non-metallic components.
  - Net shape.
  - Binder jet process: build, cure, sinter.
  - Parts have inherent 60 %TD, which is normally a disadvantage in metal parts can be leveraged as an advantage in production of ZrC at 60%TD.
  - https://www.youtube.com/watch?v=wRj44e8D-xk



ZrC Tie-Tube Insulator

ExOne M-Flex Binder-Jet at ORNL MDF

Conclusions

- AM is potentially applicable to a number of NTP components.
  - Turbopump: turbine, impeller, housing (existing efforts).
  - Regnerative cooled nozzle (existing efforts).
  - Lines, ducts, valves, flow baffle, pogo accumulator (existing efforts).
  - ZrC tie-tube sleeve insulators and core slats.
  - AlBeMet Injectifold.
  - B_4C neutron shield segments.
  - Others?
- Much of this development is already underway for conventional chemical propulsion engines.
  - R&D efforts should be focused on NTP specific materials/components.

Recommendations for Future Work

- Powder suppliers for NTP specific materials are needed.
- NTP specific material build parameters lacking.
- ZrC production investigation.
  - Optimize build parameters to produce 60%TD with desired mechanical and thermal properties.
  - Demonstrate production with binder-jet of net-shape parts.
  - Develop post process heat treatments to achieve sub-stoichiometry.
- AlBeMet 162 production investigation.
  - Demonstrated electron-beam welding (EBM candidate).
  - Work currently being done on laser welding (SLM candidate).
  - Powder is a health hazard and will require special handling and dedicated machines.

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- The opinions expressed in this presentation are those of the author and do not necessary reflect the views of NASA or any NASA Project.

Questions?