Metal 3D Printing of Low-NOX Fuel Injectors with Integrated Temperature Sensors

Award No: DE-FE0026330

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Project Information

- **Project Title:** METAL THREE DIMENSIONAL (3D) PRINTING OF LOW-NITROUS OXIDE (NOX) FUEL INJECTORS WITH INTEGRATED TEMPERATURE SENSORS
- **Award No:** DE-FE0026330
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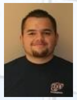
- **Period pf Performance:** 10/01/2015-09/30/2018
- **Project Amount:** $250,000
- **Research Team:** Jorge Mireles and Jaime Torres
- **UTEP Research Centers:** W. M. Keck Center for 3D Innovation
  NASA MIRO Center for Space Exploration and Technology Research

The University of Texas at El Paso

Outline

- Project Information
- Objectives
- Background
- Technical Methods
  - Task Descriptions
- Timeline
- Milestone Log
- Decision Points

Objectives

- **Objective 1: Development of design methodologies for Low-NOx fuel injectors with embedded temperature capabilities for Electron Beam Melting (EBM) based 3D Manufacturing.**
  - Design for Additive Manufacturing: Component Design Features; Geometric Tolerance and Dimensioning
  - Design Features; Process Parameters and Part Quality

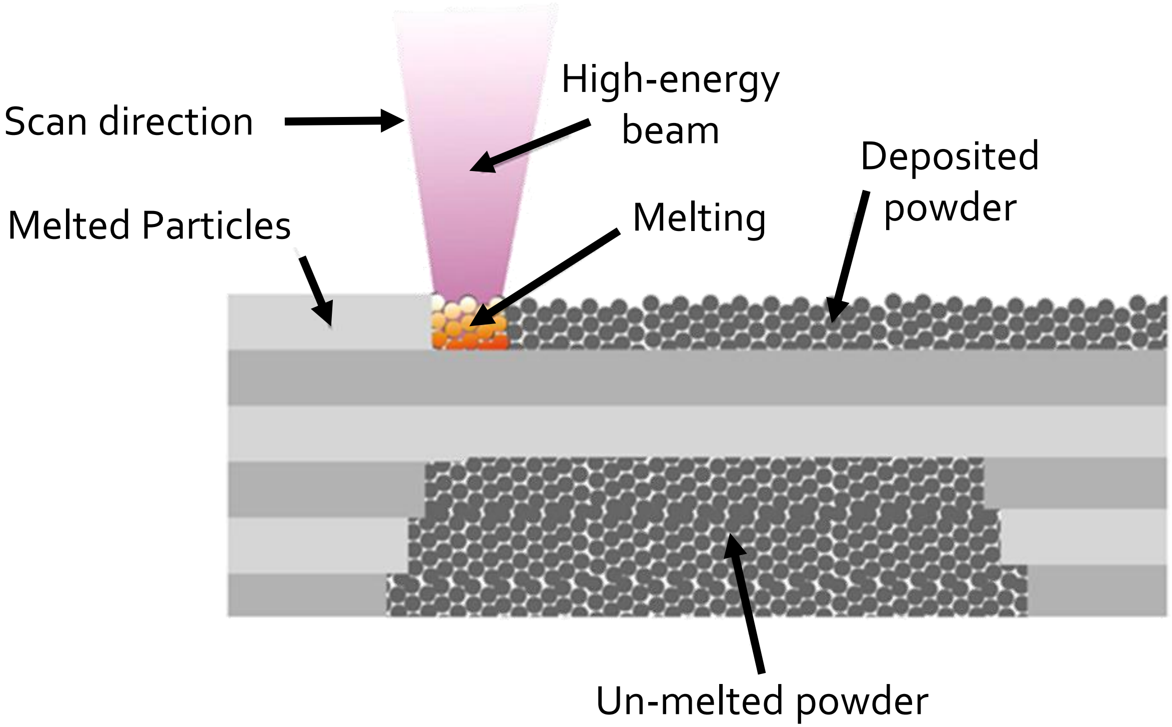
- **Objective 2: Development of optimum EBM process parameters and powder removal techniques to remove sintered powder from internal cavities and channels of Low-NOx fuel injectors with embedded temperature sensors.**
  - Dry ice blasting, ceramic blasting, water jetting, chemical etching, ultrasonics (patented technology by UTEP – U.S. Patent No. 8,828,311 B2), and megasonic baths

- **Objective 3: Testing of the EBM fabricated Low-NOx fuel injector with integrated temperature measurement capabilities in a High Pressure Laboratory Turbine Combustor**
  - Functionality and operability in a realistic environment (combustor pressure up to 1.2 MPa (~175 psi) using natural gas)

Background

Additive manufacturing is a process of creating parts directly from a computer model in a layer-by-layer fashion

- *Seven classes of technologies*
  - Material Extrusion
  - Material Jetting
  - Binder Jetting
  - Directed energy deposition
  - Vat photopolymerization
  - Sheet lamination
  - **Powder bed fusion**



Background
Electron Beam Melting Technology

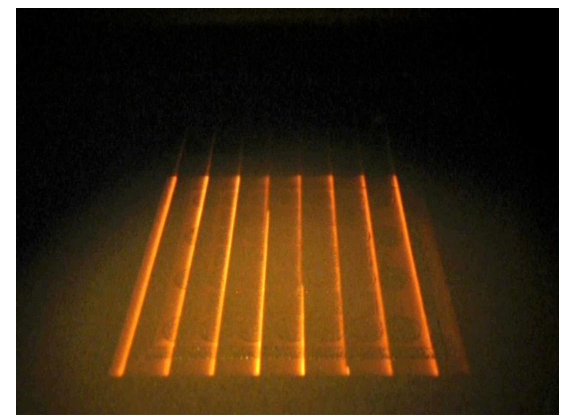
S12

(modified for high temperatures)

A2

Two Build Tanks
200 x 200 x 350mm
(7.8 x 7.8 x 13.75 in)
Ø = 300mm, h = 200mm
(Ø = 11.81, h = 7.8 in.)

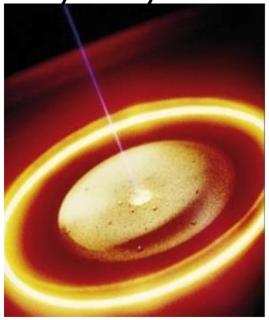
One Build Tank
200 x 200 x 180mm
(7.8 x 7.8 x 7.0 in.)

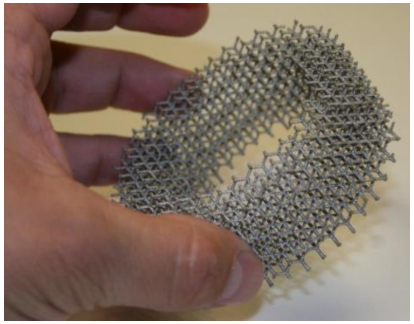


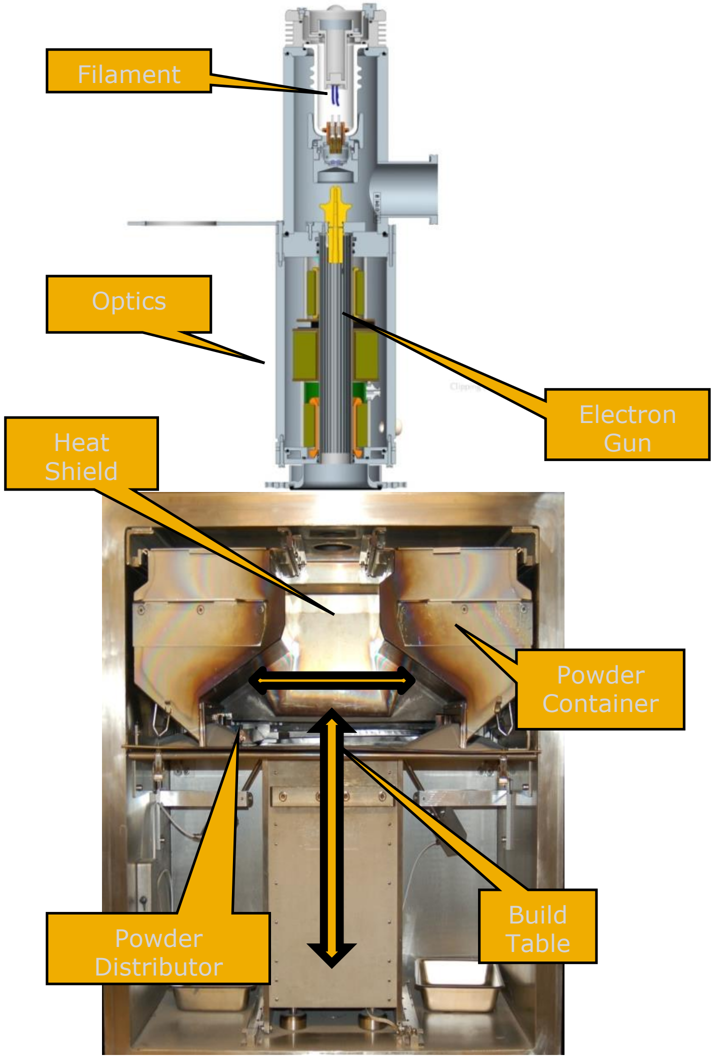
Background

EBM Process Parameter Development

- Arcam Released Materials
  - Titanium Ti-6Al-4V
  - Titanium Ti-6Al-4V ELI
  - Titanium Grade 2
  - Cobalt-Chrome, ASTM F75
- Research Materials
  - Ti-6Al-4V
  - TiAl
  - CoCrMo
  - Rene alloys
  - Inconel 625
  - Inconel 718
  - Copper
  - Niobium
  - Iron based alloys
  - Other proprietary alloys







Background

Sensors Integration

- **Sensors can be embedded (without post-production component modifications) in EBM-fabricated components through two distinct processes:**
  - Stop and Go of the fabrication process which allows sensor placement within a cavity during fabrication where the process is allowed to continue upon sensor placement
  - Post-integration of sensors in customized compartments selectively built within the part.

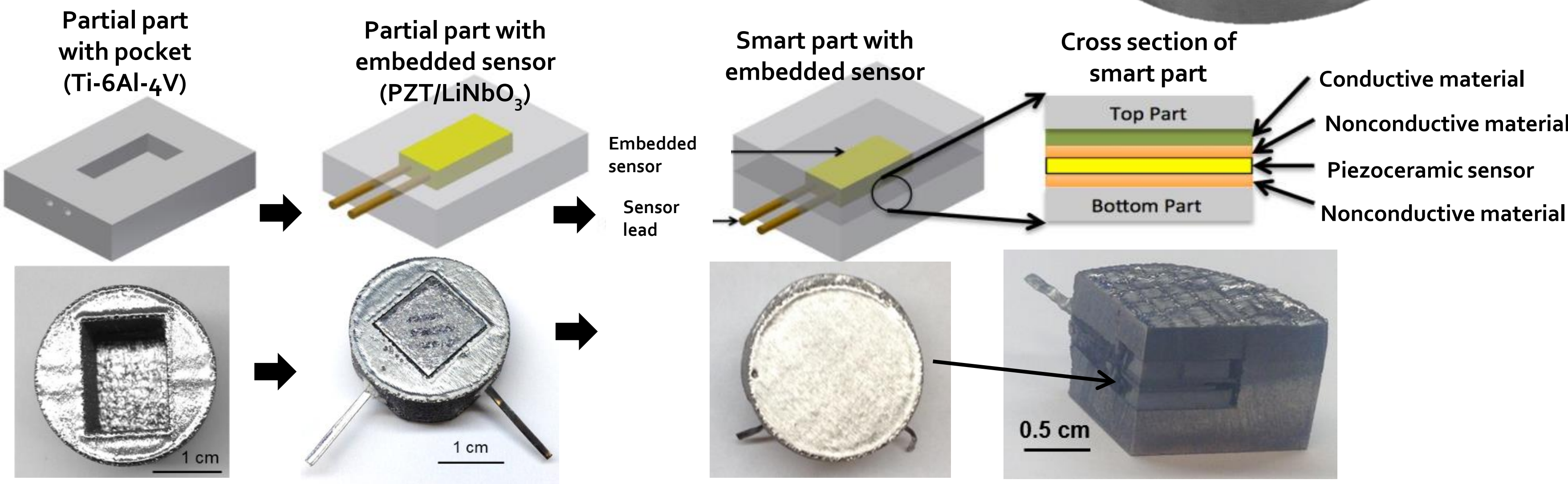
- **The Stop and Go process requires an extremely accurate re-alignment of the powder-bed during the restart process.**
  - Metallization and shorting of sensors due to a considerable high temperature of the EBM process creates significant fabrication challenges and limit the types of sensors that can be embedded.

- **The Post-Integration of sensors is a practical alternative for components that can be effectively designed and fabricated with pre-built complex sensor compartments without the need for post-production component modifications.**

Background
Stop and Go

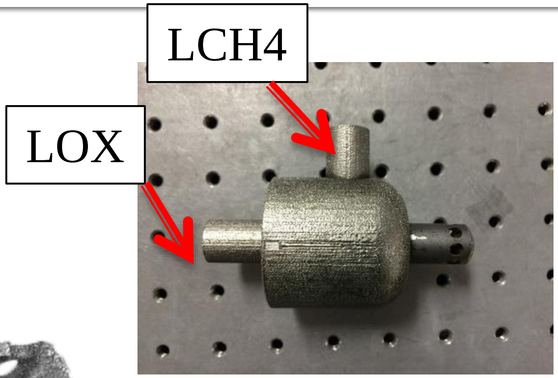
demonstration

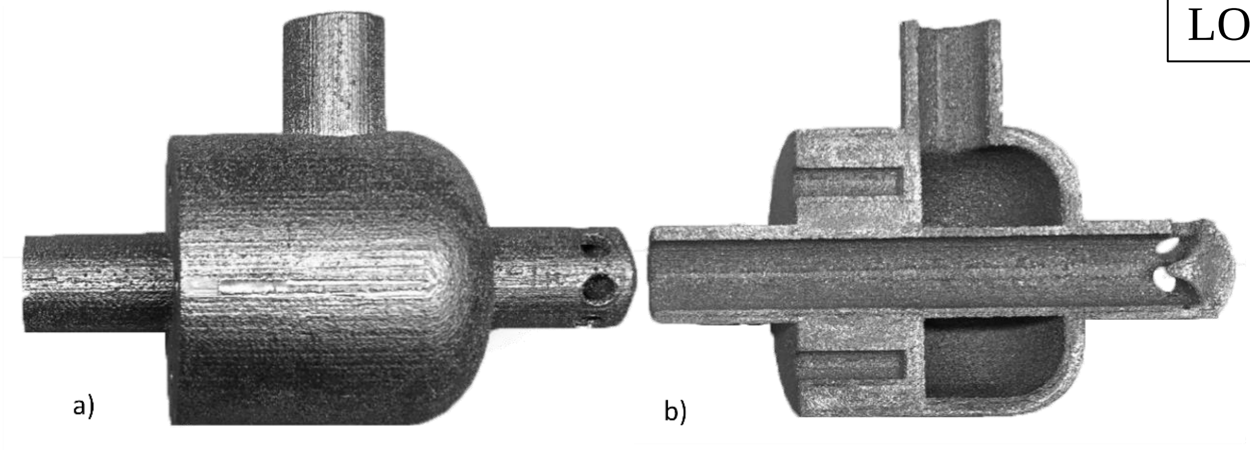
- **Metallic components with embedded piezoceramic sensor for high efficiency energy system**
  - Fabrication of complex structures
  - Real time performance feedback from desired location
  - Structural health monitoring

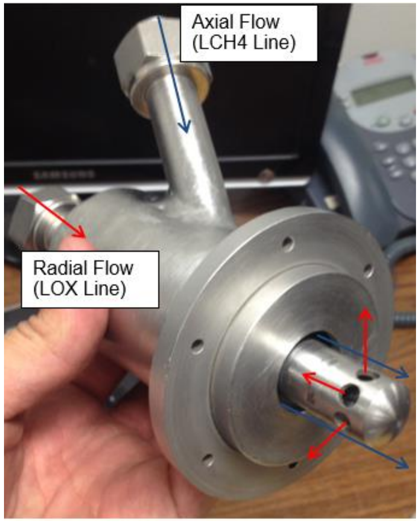


Background

Post-Integration





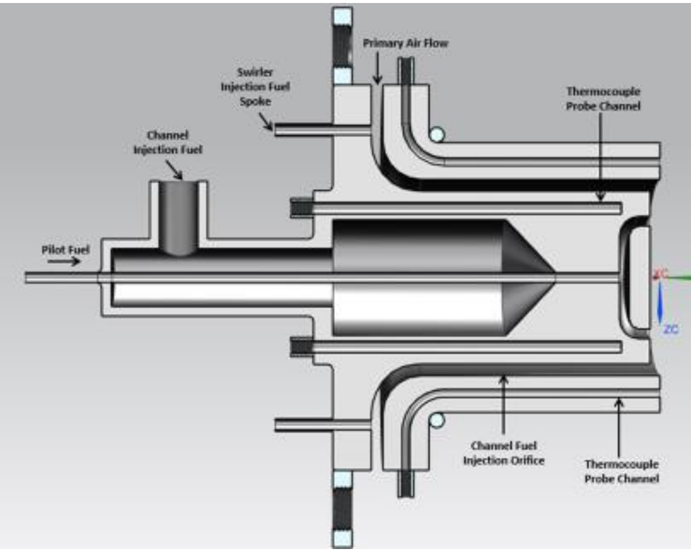


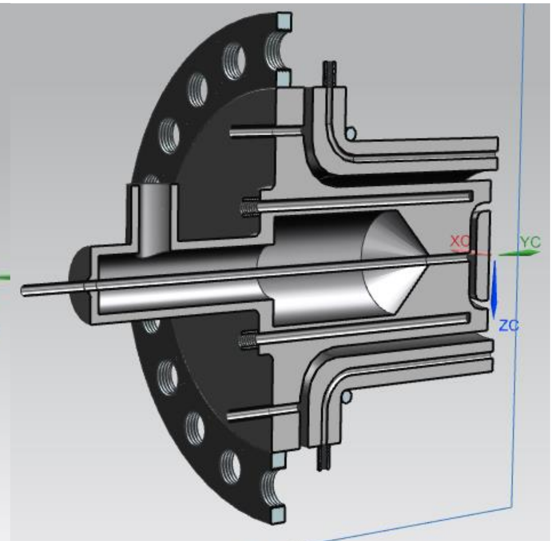
EBM Fabricated Pintle-Injector for a 9 KN LO_2/Methane Rocket Engine

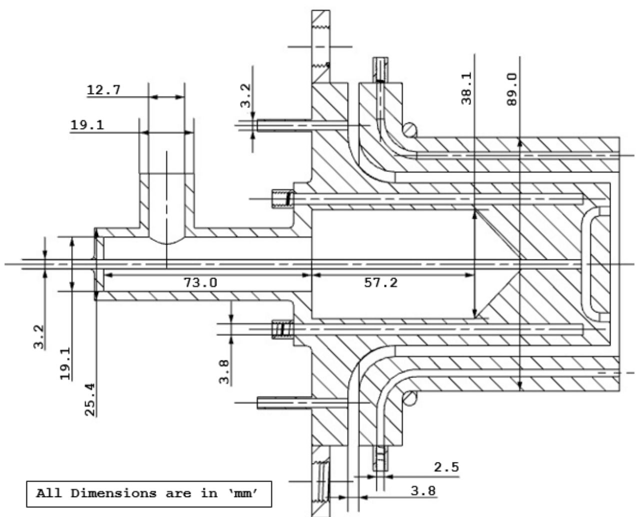
Challenges

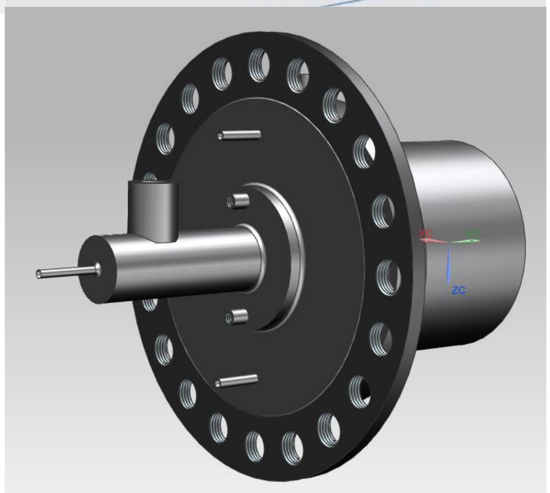
- **Certain challenges are foreseen when creating internal cavities/channels within AM parts fabricated using powder bed fusion AM technologies such as electron beam melting**
  - Geometric Tolerance and Dimensioning of internal cavities and channels
  - Removal of powder from internal channels/cavities as the powder to be removed has been lightly sintered during the fabrication process

Technical Methods









- Test Component: Low-NO_x fuel injector with integrated temperature sensors (derived from the Solar Turbine low-NO_x fuel injector for natural gas)
  - Ceramic Insulated High Temperature Thermocouple: OMEGA® Nextel/XC-14-J-12
  - Inconel 718 and Inconel 625
  - 3.2 to 3.8 mm diameter slender circular channels

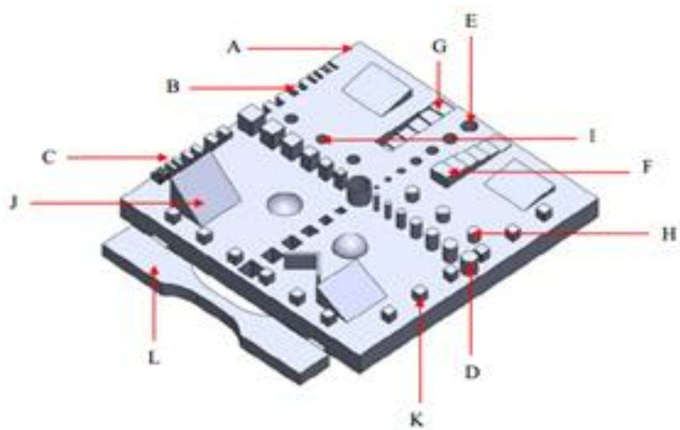
Task Descriptions

Objective 1: Development of design methodologies of Low-NOx fuel injectors with embedded temperature capabilities for EBM based 3D Manufacturing.

Task 1.1: Fabrication of test part for technology evaluation

- parts will be fabricated (Inconel 718, Inconel 625, and/or Titanium alloys) to assess the dimensional accuracy of EBM-fabricated parts
- various geometric shapes and features that can be potentially implemented in fuel injectors.

Letter	Feature	Factor To be Tested
A	Square base	Dimensional accuracy
B	(+) Lateral ridges	
C	(-) Lateral ridges	
D	(+) Descending cylinders	
E	(-) Descending cylinders	
F	(+) Staircase	
G	(-) Staircase	
H	(+) Cylinders	
I	(-) Cylinders	
J	Ramps	Surface Roughness
K	Rectangular prisms	Linear displacement error
L	Tensile Bar	Ultimate tensile strength



Task Descriptions

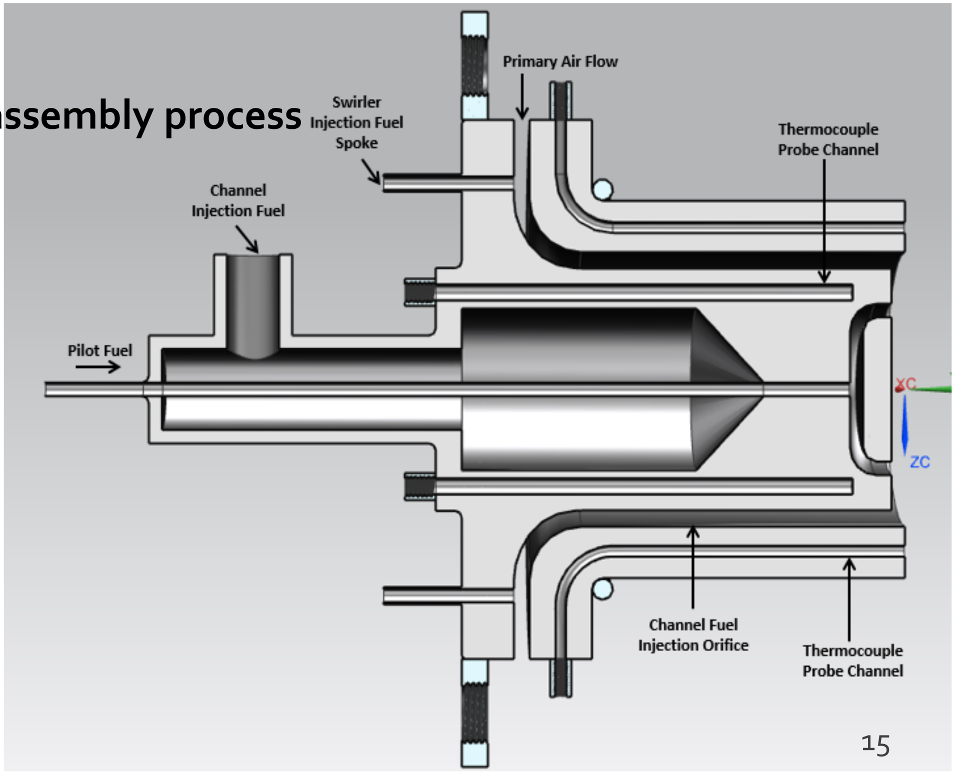
Task 1.2: Evaluation of test parts

- Dimensional accuracy
  - OGP Smartscope Flash 250
  - Mitutoyo SJ-201P surface roughness tester
- Mechanical testing will be completed using the specification of the E8/E8M ASTM standard

Task Descriptions

- **Task 1.3: Design for AM of Low-NO_x fuel injector**
  - Develop designs to fabricate the complete injector (using Inconel 718, Inconel 625, and Titanium alloys) in a single EBM build run.
  - The task will run in parallel to the powder removal tasks (Objective 2)
  - Final design will be created upon determining the appropriate powder removal strategies

- **Task 1.4: Designs for sensor integration as an assembly process**
  - Cavities for placement of sensors
  - Implementation of fasteners or caps

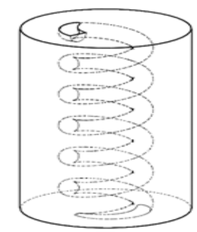


Task Descriptions

Objective 3: Testing of the EBM fabricated Low-NOx fuel injector with integrated temperature measurement capabilities in a High Pressure Laboratory Turbine Combustor

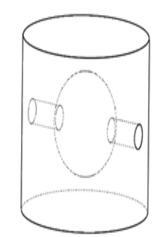
Task 2.1: Powder removal for internal channels

- methods for powder removal to be explored include, but are not limited to, dry ice blasting, ceramic blasting, water jetting, chemical etching, ultrasonics, and megasonic baths
- 3 parts of each sized cavity will be fabricated and tested with each method



Task 2.2: Powder removal for internal cavities

- To determine the appropriate number of outlets and outlet size that allow improved powder removal



Task 2.3: Process parameter modifications for improved optimal powder sintering

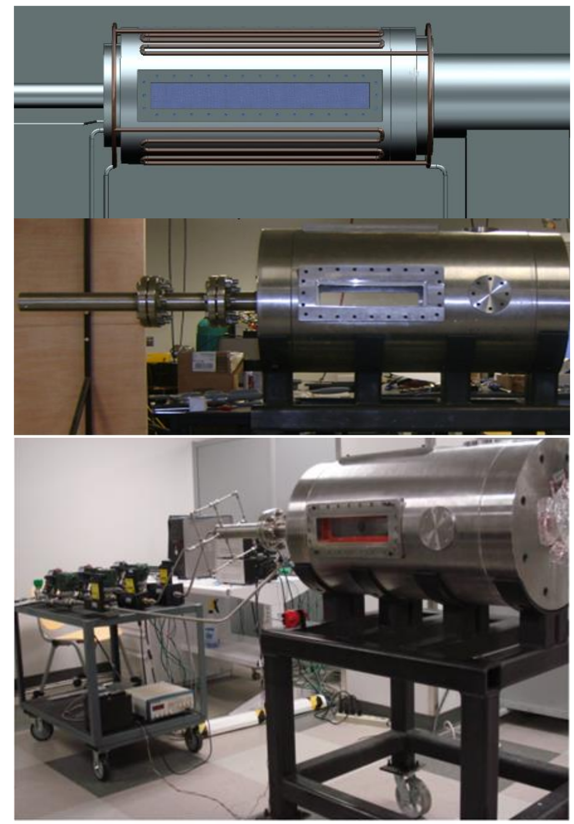
- To change the heat input to the sintered powder which consists of changing parameters such as beam speed, beam power, and beam focus.
- An improved parameter set would allow for the powder bed to become more or less sintered and easier to remove via the powder removal techniques

Task Descriptions

Objective 3: Testing of the EBM fabricated Low-NOx fuel injector with integrated temperature measurement capabilities in a High Pressure Laboratory Turbine Combustor

Task 3.1: Functionality Assessments of the injector in a High Pressure Combustion Environment

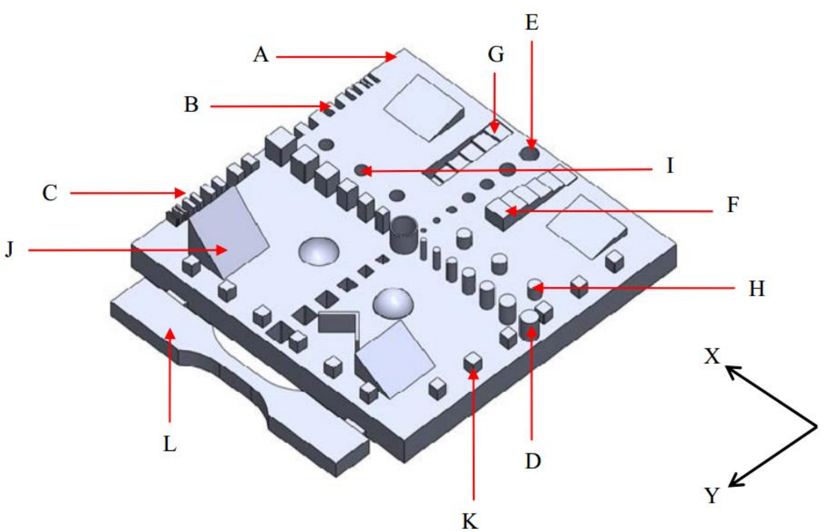
- Functionality of the injector with integrated temperature sensors will be evaluated using a Dynalene™ cooled high-pressure turbine combustor
- AM fabricated injectors will be tested at a combustion pressure of 1.2 MPa (~175 psi) using natural gas (CH_4)
- The functionality and durability of the embedded sensors will evaluated during the test runs.
- The post-run analyses of mechanical properties such as hardness and the tensile and compressive moduli of injector test articles will be measured to understand the stability and tolerance of AM fabricated components under extreme thermo-chemical conditions.



High Pressure Turbine Combustor

Current Status

Test part and its design features



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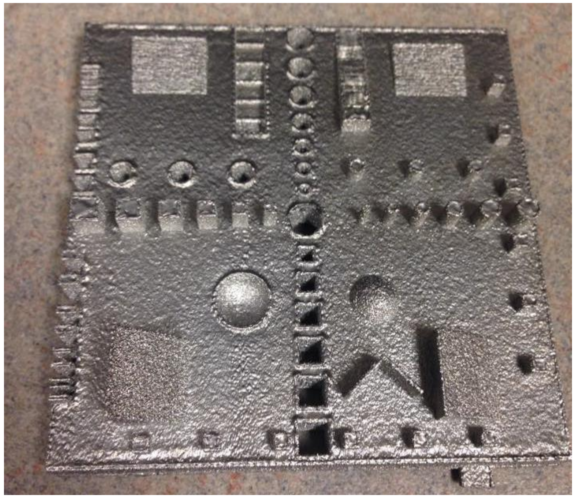
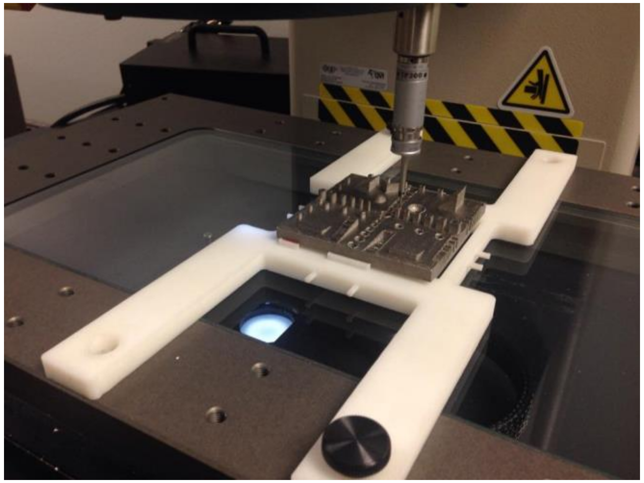
G	(–) Staircase	
H	(+) Cylinders	
I	(–) Cylinders	
J	Ramps	Surface roughness
K	Rectangular prisms	Linear displacement error
L	Tensile Bar	Ultimate tensile strength

- EBM-fabricated parts of various geometric shapes and features will be tested for dimensional accuracy, surface roughness and linear displacement.



Tests performed

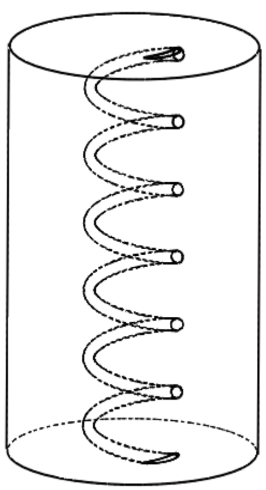
- **Dimensional Accuracy-** utilizing the OGP Smartscope Flash 250 to measure the various geometric shapes and features.
- **Surface roughness-** using a Mitutoyo SJ-201P surface roughness tester.



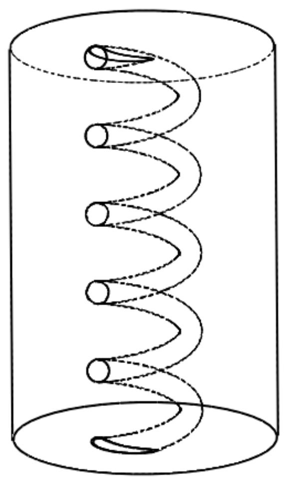
Additional Parts

- Additional pieces will be fabricated with spiral internal channels of diameters 2mm,4mm,8mm and 10mm to test powder removal techniques

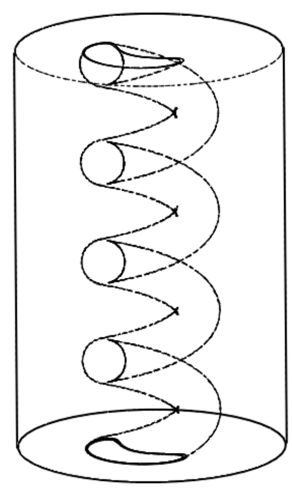
2mm



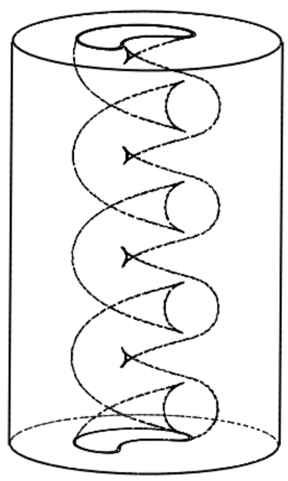
4mm



8mm

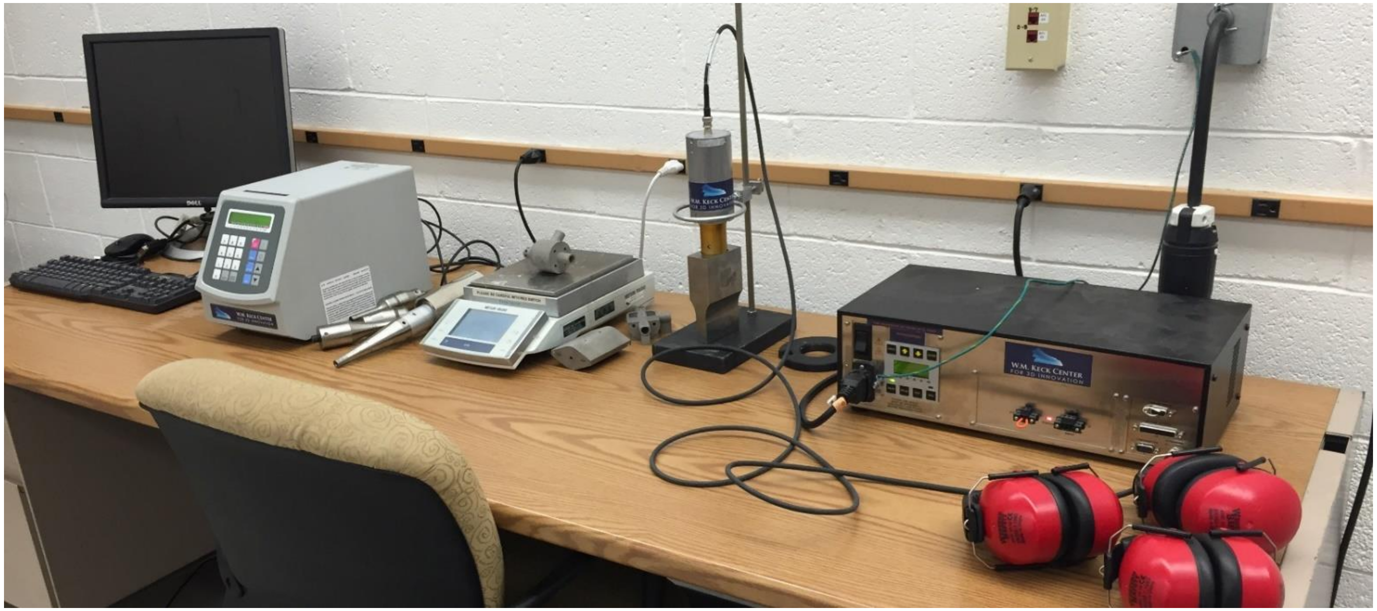


10mm



Powder removal

- Powder bed fusion allows the creation of complex structures; however, structures that reside powder within internal features needs to be removed
  - A key topic in this research is to explore powder removal methods to enable access to internal cavities
  - Initial powder removal method to be explored will be the use of ultrasonic energy



Powder removal method

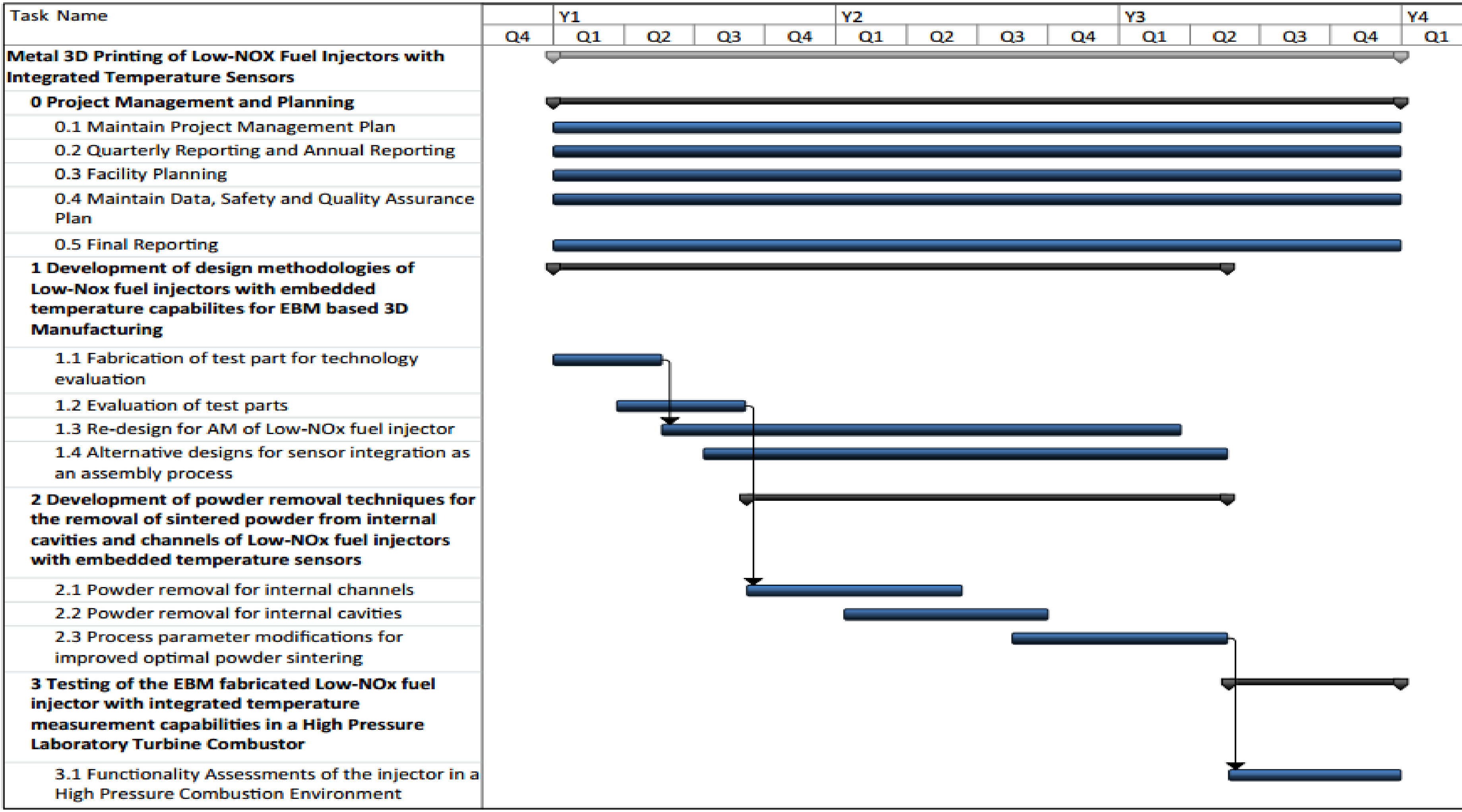
Document part weight versus CAD comparison

Evaluate entrapped powder locations

Apply ultrasonic energy and recycle powder

- Patented by UTEP for powder removal under U.S. Patent No. US 8,828,311 B2
- Has been proven to remove powder from a variety of channel sizes without the need of fluids

Timeline


Task Name
Y1
Y2
Y3
Y4
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Metal 3D Printing of Low-NOX Fuel Injectors with Integrated Temperature Sensors
0 Project Management and Planning
0.1 Maintain Project Management Plan
0.2 Quarterly Reporting and Annual Reporting
0.3 Facility Planning
0.4 Maintain Data, Safety and Quality Assurance Plan
0.5 Final Reporting
1 Development of design methodologies of Low-Nox fuel injectors with embedded temperature capabilites for EBM based 3D Manufacturing
1.1 Fabrication of test part for technology evaluation
1.2 Evaluation of test parts
1.3 Re-design for AM of Low-NOx fuel injector
1.4 Alternative designs for sensor integration as an assembly process
2 Development of powder removal techniques for the removal of sintered powder from internal cavities and channels of Low-NOx fuel injectors with embedded temperature sensors
2.1 Powder removal for internal channels
2.2 Powder removal for internal cavities
2.3 Process parameter modifications for improved optimal powder sintering
3 Testing of the EBM fabricated Low-NOx fuel injector with integrated temperature measurement capabilities in a High Pressure Laboratory Turbine Combustor
3.1 Functionality Assessments of the injector in a High Pressure Combustion Environment

Milestone Log

Mile-stone	Title	Description	Success Metrics	Reporting	Qtr.	Date	Complete
Budget Period 1							
M1	Updated Project Management Plan	Complete plans for Facility, Resources, Quality, Safety, Documentation Management, etc.	Predecessor of all following tasks	Report Plan delivered to DOE PM	Q1-Y1	TBD	TBD
M2	Kickoff Meeting	Review of objectives, technical and managerial approach and other facets of project	Predecessor for tasks	Presentation delivered to DOE PM	Q1-Y1	TBD	TBD
M3	Development design metrics for EBM-fabricated parts	Design criteria and limitations for low-NOx fuel injectors fabricated using EBM	Evaluation of test parts	Summarized in Quarterly Report	Q3-Y1	TBD	TBD
M4	Development of powder removal strategies	Determination of methodologies required for proper powder removal	Successfully removing powder for internal cavities	Summarize results in Quarterly Report	Q3-Y2	TBD	TBD
M5	Fabrication of instrumented low-NOx fuel injectors	Fabricated low-NOx fuel injectors using EBM and containing cavities or channels for sensors	Achieving fabrication of re-engineered low-NOx fuel injector	Summarize results in Quarterly Report	Q1-Y3	TBD	TBD
M6	Final testing of Low-NOx fuel injectors	Results pertaining to embedded sensors within low-NOx fuel injectors enabled by EBM	Evaluation of test data	Summarized in Quarterly Report	Q4-Y3	TBD	TBD

Success Criteria at Decision Points

DECISION POINT 1

Parameter: Development of design metrics for EBM-fabricated parts

Components: Tasks 1.1- 1.3

Bearing: The results from this component will determine the design constraints for the rest of the project

Planned Assessment: Q3-Y1

Successor: Task 1.3 Designs for sensor integration as an assembly process

DECISION POINT 2

Parameter: Development of powder removal strategies

Components: All previous tasks and Task 2.3

Bearing: Will demonstrate viability of using AM to fabricate low-NOx fuel injectors

Planned Assessment: Q4-Y1

Successor: Task 3.1-Testing and evaluation

Questions ?

Thank You

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