MOOG

Additive Manufactured Parts for Flight Critical Applications

George Small
Principal Engineer
Moog Aicraft Group
Moog Inc.
East Aurora, New York

Moog Inc.

- Founded in 1951 by Bill Moog
- Medium-size, global company
  - $2.5B sales in FY'16E
  - 100+ locations in 28 countries
  - Over 11,000 employees
- Reputation for high quality and technical excellence

2016E Revenue = $2.5B USD

Aircraft	Space & Defense	Industrial	Components	Medical
$1,087 MM / 43%	$384 MM / 15%	$524 MM / 21%	$415 MM / 16%	$122 MM / 5%

Additive Manufacturing at Moog

Moog Additive Manufacturing Center

- Moog Additive Manufacturing Center located at Company headquarters in New York

- AMC Charter – Research oriented
  - Materials Understanding
  - AM Process Development
  - Make Parts(!)
  - Communicate & Educate
  - Business Impacts

ADDITIVE MANUFACTURING CENTER

Core Staff:

- Engineering
  - Dr. Paul Guerrier – AMC Manager
  - George Small – Principal Engineer
  - Chris Layer – Principal Engineer
  - Jason Jones – M&P Engineer
  - Ian Brooks – Principal Engineer
  - John Calnan – Assoc. Engineer
- Manufacturing
  - Connie Buynacek – Advanced Mfg Engineering
  - Richard Buchanan – Sr. Manufacturing Engineer
  - Brion Dormer – Manufacturing Engineer
  - Tom Heyden – Manufacturing Engineer
  - Steve Delzer – DOE Statistical Expert
  - Kristi Weaver – Quality Engineer
- Business Development
  - Robert Morgan – Business Development
  - Jim Regenor – Business Development
  - Kai Szakmary – Finance
- Design Engineering
  - (10) US
  - (10) Europe
  - (5) India

Founding Moog AMC Team

Moog AMC Facilities

Moog Additive Manufacturing Center

(2) Renishaw, (1) EOS LPBF Machines

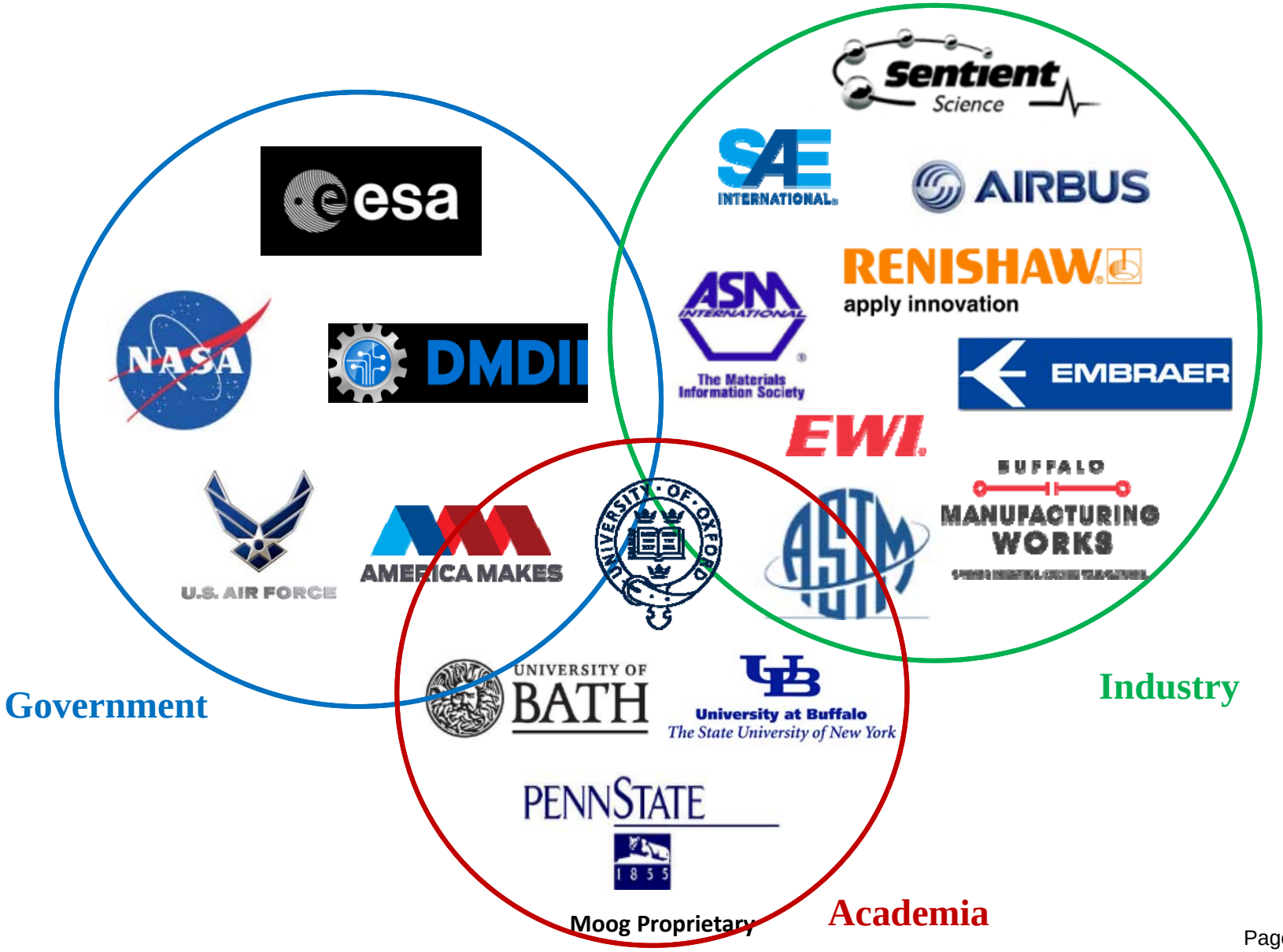
Wide Throat Wire EDM

Northstar X5000 CT

Personal Protection Equipment

Stress Relieve Oven
Ultrasonic Cleaner
Grit Blast

Partnerships and Collaborations



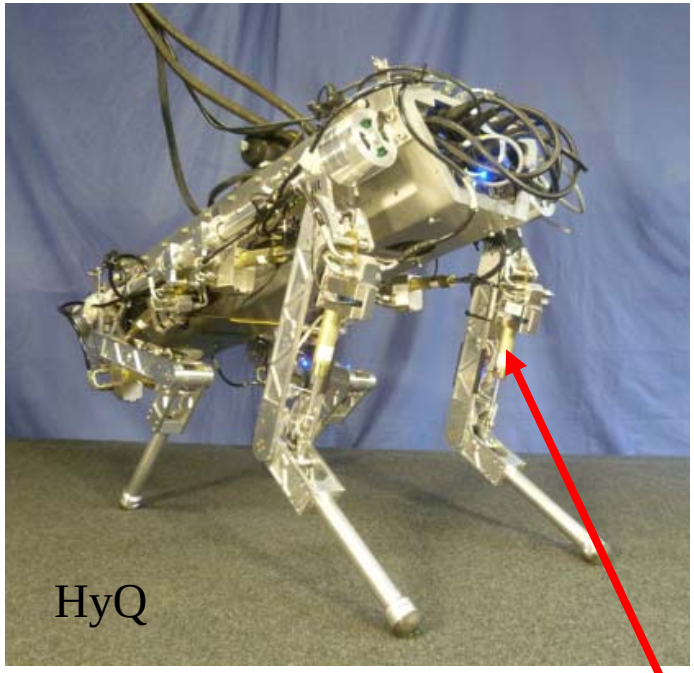
2015 Moog Acquisition: Linear AMS

- December 2015 Moog Inc. acquired 70% of Linear Mold and Engineering
- 130 Employees, located in Livonia, Michigan
- Services
  - Additive Manufacturing: 3D Metal Printing
  - Conformal Cooling
  - Plastic Injection Molds and Tooling
  - Injection Mold Part Manufacturing
  - Product Design
  - Models & Fixtures
- 17 AM Machines - metal powder bed fusion
  - 8 SLM 280
    - 5 Dual Laser, 3 Single Laser
  - 4 EOS M270
  - 3 EOS M280
  - 2 EOS M290
- Quality Certifications:
  - ISO9001
  - AS9100
  - TS16949
  - ISO 13485
- Linear AMS will continue as an independent value-added Additive Manufacture Metals producer
  - Preliminary target: 80% Non-Moog, 20% Moog

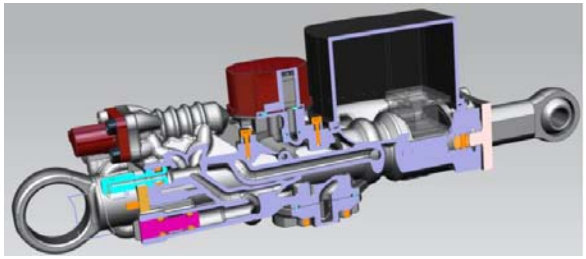
LINEAR AMS
A Moog Company

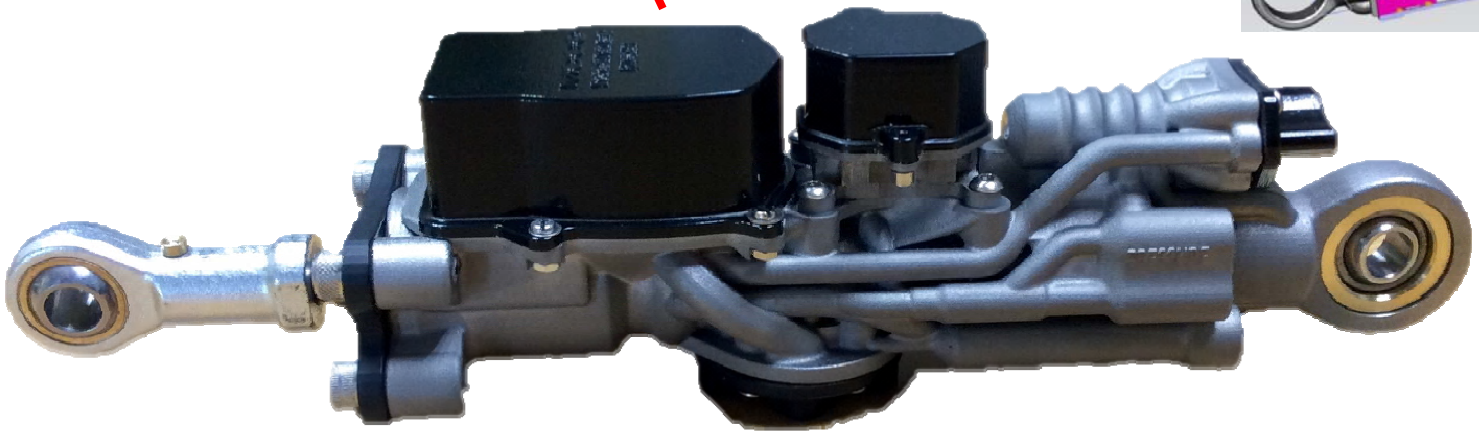
Making Parts

High Functional Density Robotic Actuator

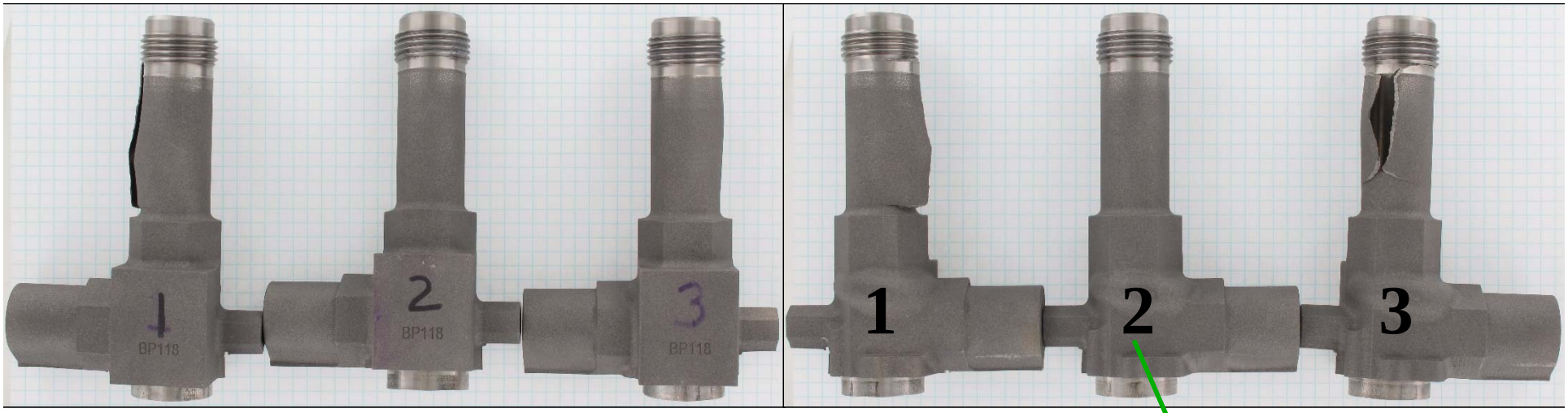


- Smart hydraulic quadruped robotic leg actuators
  - Collaboration with Italian Institute of Technology in Genoa, IT on their HyQ robotic platform
  - Local electronic force and position control

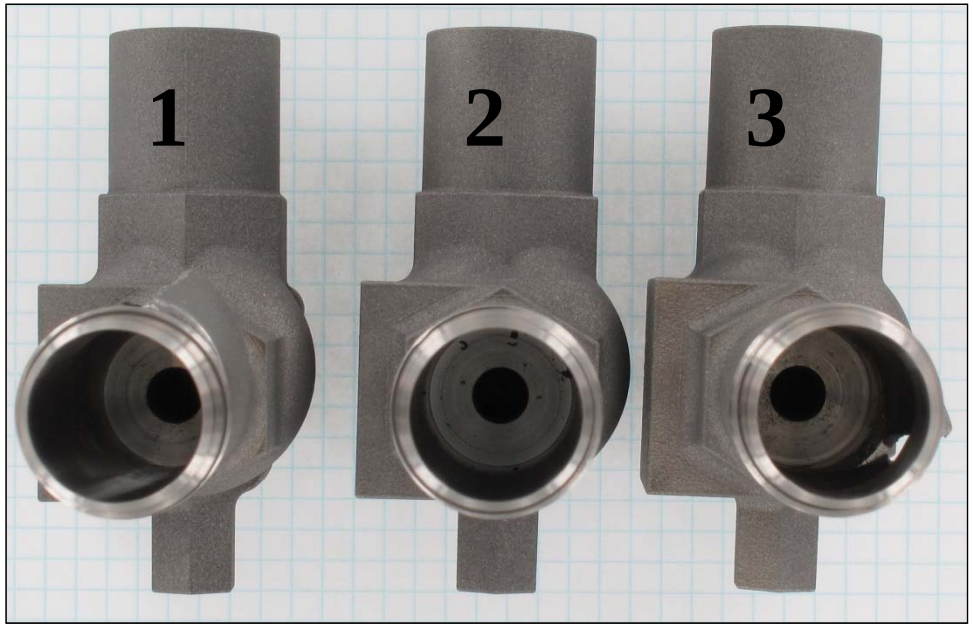




Propulsion Valve Demonstration

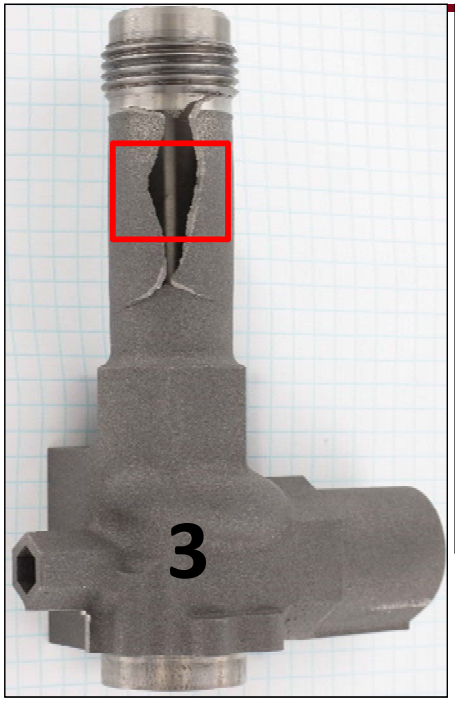


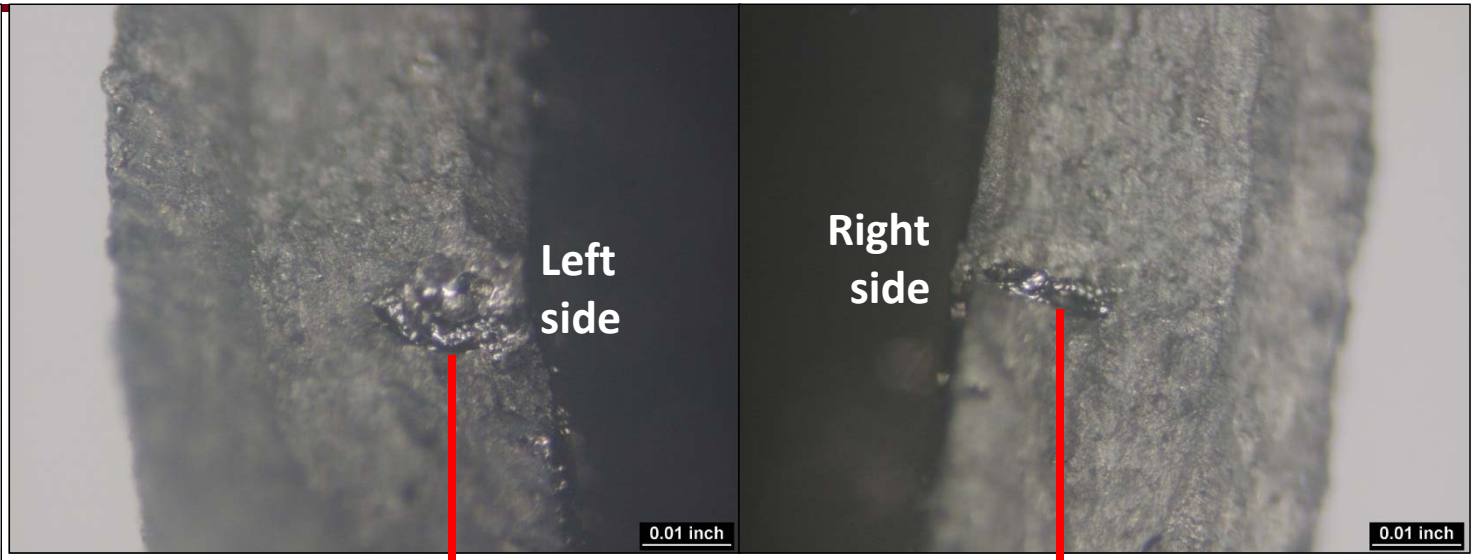
Test Pressure
20,000 psi



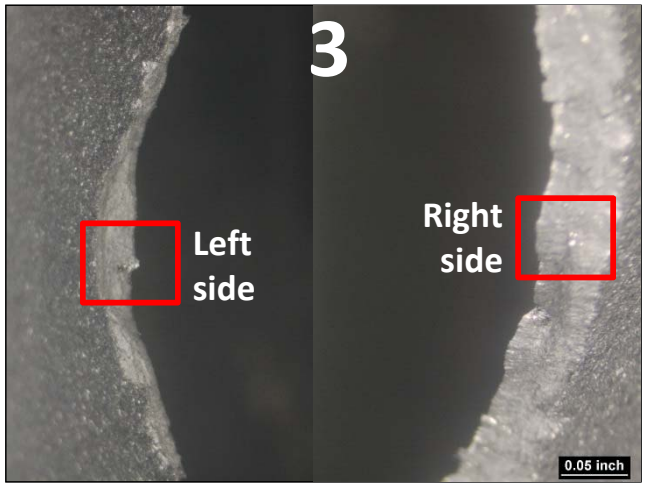
Burst Test Specimen 2 did not burst even with 0.050” wall

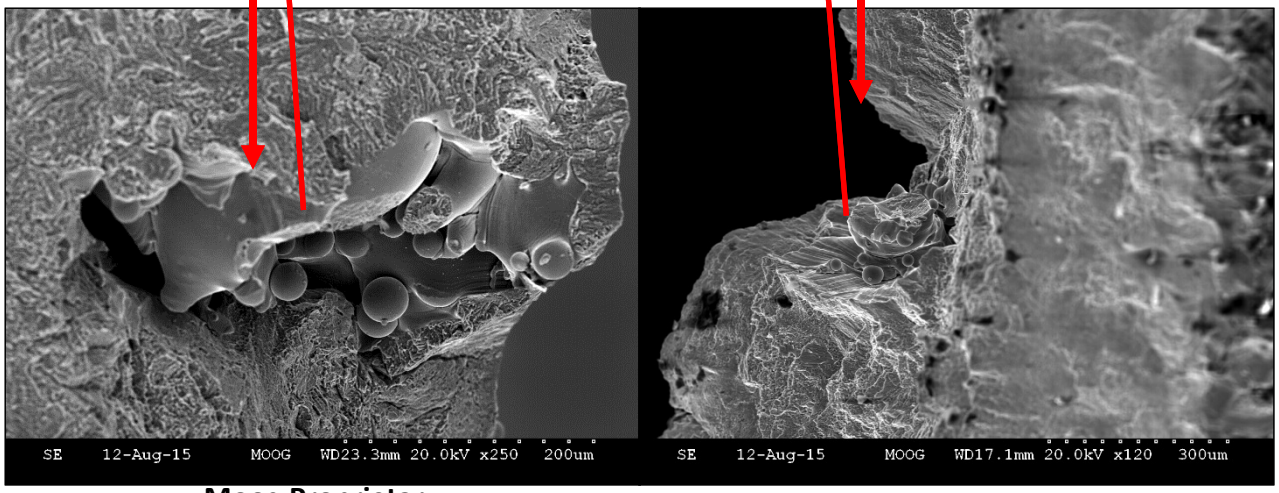
Burst Test Sample 3





void/lack of fusion initiation





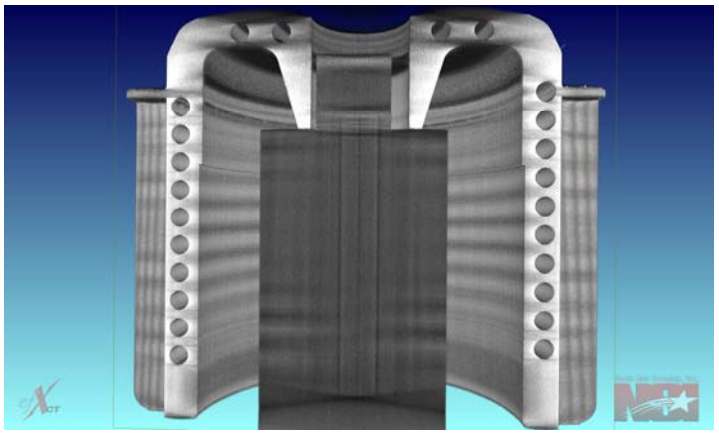
Rotating Machinery

Micro Turbine

Blower Impeller (70000 rpm)

Generator Housing

Internal Cooling



Hydraulic Manifolds and Reservoirs

Direct Drive Valves

Custom Reservoirs For Tight Packaging

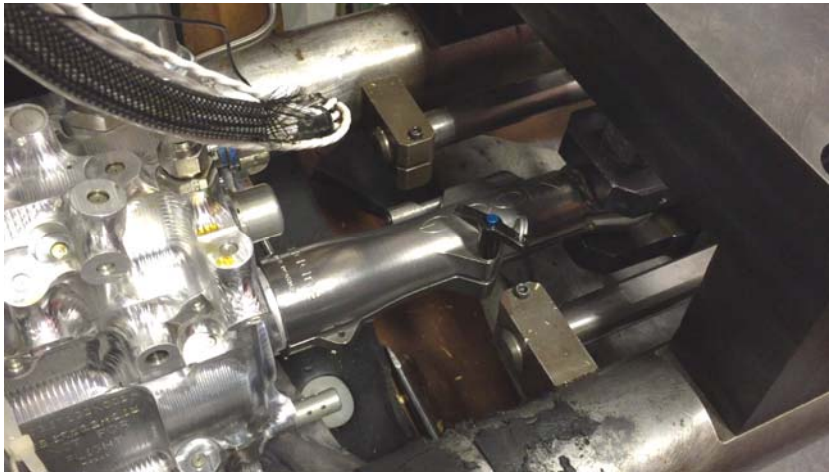
Servovalve Bodies

Control Modules

Integrated Robot Actuator Housings

Spoiler Locking Collars – Ground Equipment

Locking Collar Under Test



Embraer E2 Outboard Spoiler Cylinder Demo

- Proof of concept demonstration
  - 15-5PH stainless steel cylinder was AM printed on Renishaw AM250
  - Non-flight demonstration actuator currently being assembled using AM cylinder shown
  - Actuator will be Acceptance Tested and subject to limited endurance and fatigue testing

AM in Support of Certification

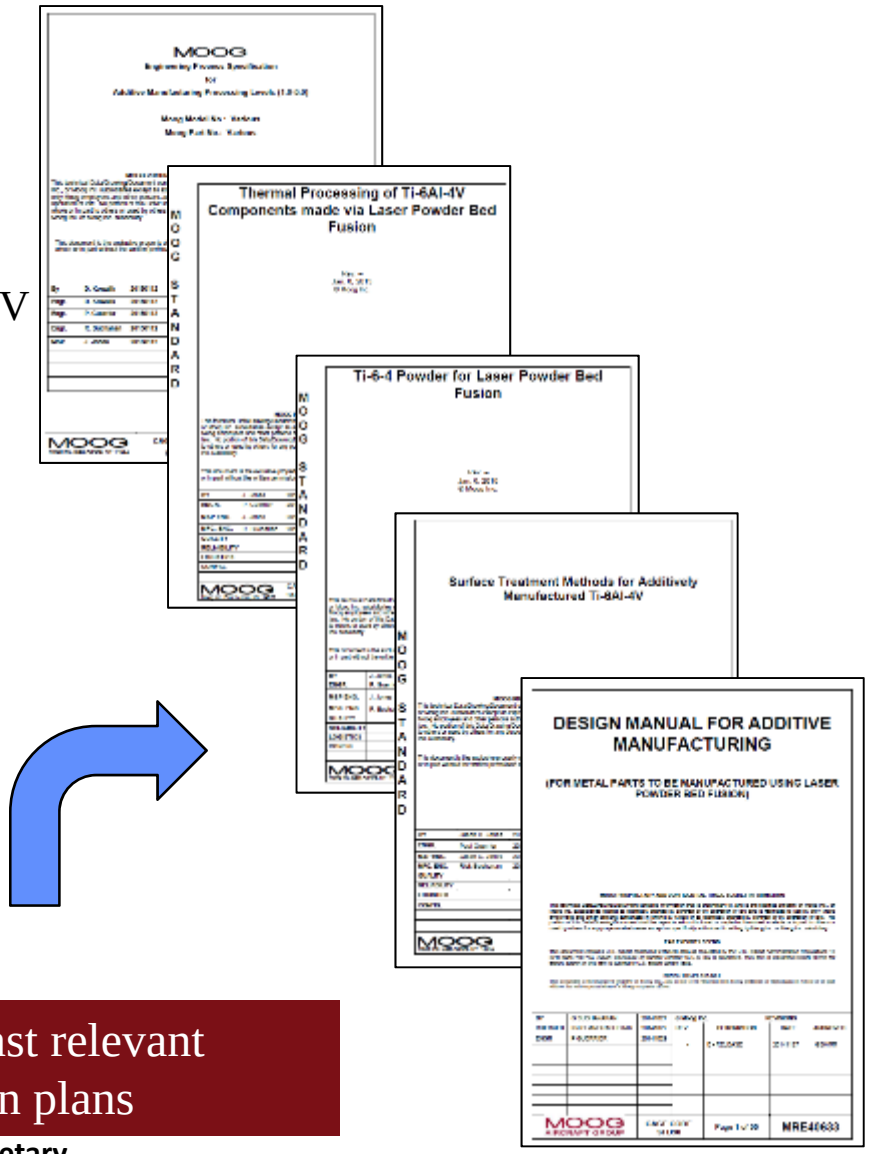
Moog Process Coverage Compliance Matrix

Common Industry Understanding or Acceptance of:	Al 2014 Cast *(common airframe alloy)*	AM Alloy *(airframe or engine alloy)*	MOOG Standards
Material and process specs	Yes	No / WIP	EMS45279:Ti, EMS45710:15-5
Design allowables • Effect of Environment • Knock down factor	Yes	No / WIP	MRE43676:Ti MRE46017:15-5
Capable NDI methods • Effect of surface finish	Yes	No / WIP	EPS47032
Characterization of material defect / anomalies types	Yes	No / WIP	MRE48189 (In Work)
Key manufacturing process control parameters and acceptable ranges	Yes	No / WIP	EPS42894
Effect of process parameters on microstructure and mechanical properties • Heat Treat • Hipping	yes	No / WIP	MRE43676:Ti MRE46017:15-5
Qualification / certification criteria	Yes	No / WIP	Point Certified Design/Process (2)

1. Table courtesy Jim Kabbara (FAA AM National Team Lead) taken from presentation by Chinh Vuong (FAA), presented to SAE Aerospace Standards Summit July 7, 2015
2. Near term plan – until appropriate industry standards are sufficiently mature

Full Cycle M&PE Process Control Documentation

- MRE40633
  - **Design** of AM components
- EPS42894
  - **Process Control** for LPBF AM
- EMS45279
  - Moog AM **Powder** specification for Ti6Al4V
- EPS43680
  - **Thermal Processing** for AM Ti6Al4V
- EPS46237
  - **Thermal Processing** for 15-5PH CRES
- EPS44249
  - **Surface Finish** Treatments, **FOD** removal
- MRE43676
  - **Material Properties** for AM Ti6Al4V
- MRE46017
  - 15-5PH CRES Material **Allowables**
- EPS47032
  - **NDI** of AM Parts



Lessons learned result in Problem Reports against relevant process documents: closed loop corrective action plans

Additive Manufacturing Enabled Supply Chains

Distributed On-Demand Manufacturing Networks

- As both an AM customer and supplier, Moog is involved in a range of forward looking use cases
- It is clear that additive manufacturing is an enabler for more digital, more connected and leaner workflows, and to “manufacturing as a service” networks.
- On-demand manufacturing networks hold the potential to benefit customers of all sizes:
  - High quality rapid prototypes
  - Entrepreneurs, start-ups with limited capital
  - Custom/semi-custom goods, “quantity of one” production runs
  - Reduce inventory and increased availability for slow-moving parts
  - Potential new weapon for AOG’s, out of production platforms

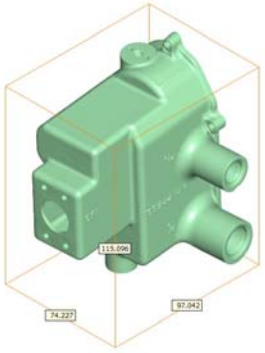
	Production Manufacturing Costs	Storage & Warehouse Costs	Import Fees, Taxes	Shipping, Transportation Costs
Standard Manufacturing	+	−	−	−
AM Manufacturing	−	+	+	+

Scan-to-Print Digital Workflow Demo

- Scan-to-print digital ‘replicator’ demonstration
  - Completed in less than 1 week end-to-end
- Digital workflow
  - Enables near net shape part replica
  - But not the same part…
- Future distributed on-demand supply chains need a solution
  - How do we verify authenticity, materials and process and maintain traceability while still supporting a more digital future state?

OE Part

uCT Scan



E-file

Print

Part

Secure, Authentic Parts for a Distributed Supply Chain

- With industry partners, Moog has been developing a technology solution for digital enabled parts supporting up to the most critical, regulated applications. This solution provides:
  - Provenance
    - History of a part through the design-manufacture-use cycle on a per part basis
  - Secure data transport
  - Digital rights management, licensable transactions
  - Authenticity of printed goods, assemblies
- Leverages blockchain shared distributed ledger technology
  - A shared database providing provenance and authenticity on a per part basis
  - Same technology family employed by Bitcoin cryptocurrency