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Research to Standards
ADDITIVE MANUFACTURING

America Makes

Specialty Workshop Series: Additive Manufacturing Data Management & Schema

Overview of NASA AM Database Efforts

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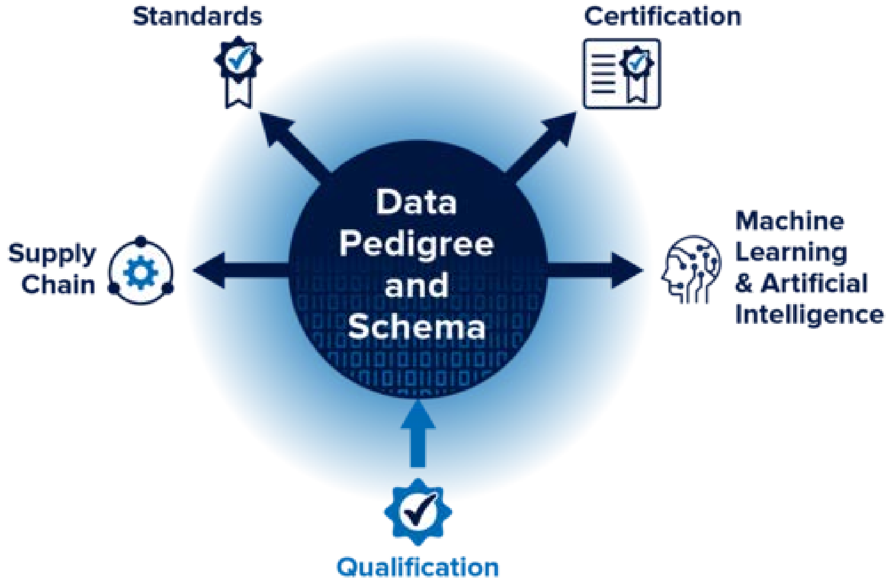
Vision for AM Data Ecosystem

Vision

- To release various statistically relevant materials properties data records characterizing the capability of additive manufacturing (AM) process. This is to satisfy the vision of sharing information with any NASA AM partner to help establish alloy specific manufacturing techniques especially for demonstration and flight hardware. Furthermore, data was intended to be widely distributed to help mature AM processes and standards.
- To enable the certification of flight hardware produced by AM processes
  - The data contained within the database is based upon a qualified metallurgical process

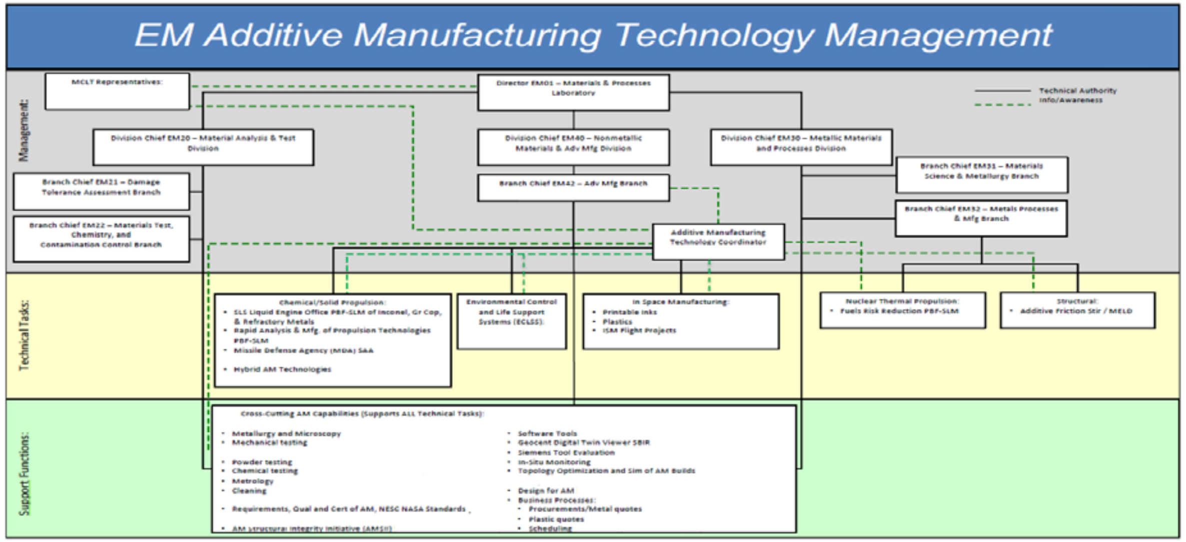


Outline

- Organizational Structure
  - Motivation and Users of AM Data
  - Criteria For Database
  - Database Structure and Attributes
- Challenges
- Future Expectations
- Gaps In Standards
- Small Case Study

Organizational Information: Internal Users & Motivation

- Multiple NASA programs and projects are interested in utilizing and providing AM data.
  - Propulsion
    - Liquid Engines
    - Solid Propulsion
  - Environmental Control & Life Support
  - In-Space Manufacturing
  - Nuclear Thermal Propulsion
  - Structures



Organizational Information: Criterial For External Usage

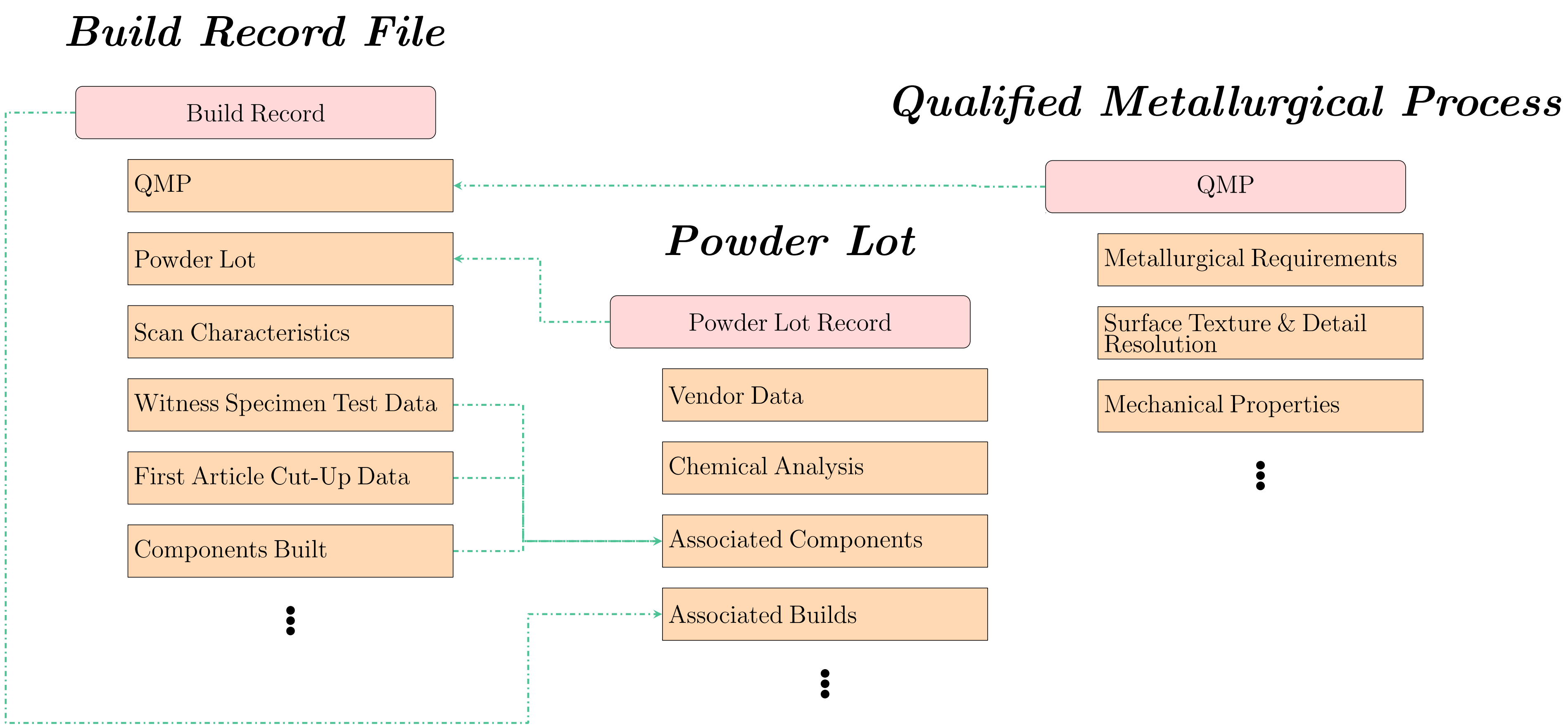
5.4.4 Criteria for the Use of External Data in the MPS

[AMR-17] Material property data generated outside the jurisdiction of this MSFC Technical Standard [MSFC-STD-3716] , such as prior industry or government data, shall meet each of the following criteria prior to incorporation into an MPS:

1. Properties are generated from material produced by the L-PBF process.
2. Authenticating records of traceability are available for the feedstock chemistry and heat treatment operations.
3. Properties are generated from material tested in a metallurgical condition (heat treatment and microstructure) equivalent to that defined by QMPs registered to the MPS.
4. Authenticating records of traceability are available that illustrate the material internal quality and final microstructure.
5. The geometry and build orientation of test specimens are defined.
6. The specifications governing the material test methods are defined.
7. The external data is provided in the form of actual test results to allow design values and PCRD criteria to be established or independently verified.
8. Demonstration that active QMP(s) produce material equivalent in microstructure and mechanical properties based on the registration process of MSFC-SPEC-3717.
9. An MUA documenting each of these criteria is approved.

[Rationale: The incorporation of prior databases for L-PBF material properties into an MPS will become standard practice as the technology matures. These criteria ensure the database contains sufficient information to follow the process controls required by this [MSFC-STD-3716] MSFC Technical Standard.]

Organizational Information: Database Structure



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Organizational Information: Database Attributes

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Build Attributes

Build Details	Scan Characteristics	Powder Lot
Record Name	Record Name	Record Name
Build ID	Material ID	Material ID
AM Technology	Build ID	Specification
Machine Vendor	Process ID	Manufacturer
Material ID	Core Laser Power	Lot Number
…	…	…

Test Data Attributes

Test Conditions	Specimen	High Cycle Fatigue	Fracture Toughness J1C	Tensile
Test Date	Sample Type	Control Mode	Fracture Valid Test	Tensile Yield Strength
Test Type	Specimen MMTF Drawing Number	Waveform	Nominal Yield Strength	Tensile Ultimate Strength
Test Specification	Specimen Nominal Diameter	Method File	Estimated Young's Modulus	Young's Modulus
Test Temperature	Specimen Nominal Width	Cycles to Failure	Nominal Ultimate Tensile Strength	Elongation, 4D
Test Media	Specimen Nominal Thickness	Stress Ratio	J1C - # pts in region A	Failure Location
…	…		…	…

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Disruptive & New Manufacturing Technology = Challenges

Challenge	Solution/Current Effort
Export Control	-
Integrated Data Acquisition	Establishment of a dynamic database within MAPTIS that interacts with existing tools to consolidate and store data.
Progression of NASA Standards to Industry Standards	Development of a NASA standard which then enables better understanding of the process allowing for the development of an industry standard
NDE & In-Situ Monitoring Data Storage and Analysis	Working with industry to develop NDE and in-situ monitoring technique that utilize the data and extract relevant information
Automated Data Capture	Exploring routes to automate data capture concerning machine state as well as actual process variables.
Agreement on What Data to Capture	Working with standards organization to establish what is “good enough”

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Disruptive & New Manufacturing Technology = Challenges

Challenge	Solution/Current Effort
Pre-cursor Geometry of Blanks/Coupons	Known-Gap
Pre-Production Article Data	Known-Gap
Characterization Build Standardization	Known-Gap

Future Expectations

- AM data ecosphere exists with a well-defined open architecture allowing collaborative pooling of non-restricted data.
- Industry standards provide sufficient process control and data requirements for qualified multiple sourced material properties
- Data development and archive methodologies are compatible with developing broad-industry databases: MMPDS, CMH-17
  - ASME, Petroleum, Nuclear
- NASA database develops to be compatible with this ecosphere

GAPS IN STANDARDS

- AM process standards lack definitive process quality metrics to ensure each qualified machine is producing AM material of specified quality.
  - Industry standards have not yet incorporated qualification metrics
- Standards do not exist for governing build geometry for material characterization
  - Production of AM material in a standard “nominal” state for the AM process
- Standards do not address specimen-to-part material capability
- Standards do not address the development of bulk material property “allowable” data versus “design values” that include AM process influence factors.

CASE STUDY

BUILD QUEUE

ID	R#	Task Name	Customer	Material	Duration	Start	Finish
1	757	med05095_redesign_1_task1	Jonathan Jones - ER50 -	Inconel 718	1 day?	Fri 9/21/12	Fri 9/21/12
2	752	ken's version of baffle	Mike Kynard	Inconel 718	1 day?	Sat 9/21/13	Sat 9/21/13
3	756	lox inducer	Randall Thornton - ER	Inconel 718	1 day?	Mon 9/24/12	Mon 9/24/12
4	759	sls nosecone	Victor Pritchett - EV33	Inconel 718	2 days?	Wed 9/26/12	Thu 9/27/12
5	756	lox inducer	Randall Thornton - ER	Inconel 718	1 day?	Thu 9/27/12	Thu 9/27/12
6	755	lox impeller	Randall Thornton - ER				
7	752	ken's version of baffle	Mike Kynard				
8	0	nasabenchmark	NCMS				
9	762	20-50-add-matl	Victor Pritchett - EV33				
10	0	nasabenchmark	NCMS				
11	755	lox impeller	Randall Thornton - ER				
12	775	rawbody-20121106	BillSadowski - ER33				
13	752	1/3 scale baffle	Mike Kynard				
14	755	lox impeller	Randall Thornton - ER				
15	771	10-22-valvebody-section	Travis Davis - ER				
16	792	90m13891-9-water-exit-fuel	Sandy Greene - ER32/Darr				
17	791	SLS-ADO-NDE-Blank-v1.2b	David Brown - EM20				
18	0	005by090grid	Jim Knox - ES62				
19	0	MATERIAL CHANGE - Aluminum					
20	777	1-mesh-hex-020by200by35deg	Jim Knox - ES62				
21	777	1-mesh-hex-020by200by35deg	Jim Knox - ES62				
22	777	1-mesh-hex-020by200by35deg	Jim Knox - ES62				
23	777	1-mesh-hex-020by200by35deg	Jim Knox - ES62				
24	803	030by090grid	Jim Knox - ES62				
25	801	015, 020, 025 by 090 grid	Jim Knox - ES62				
26	802	008, 010,012 by 090 grid	Jim Knox - ES62				
27	804	015by045	Jim Knox - ES62				
28	0	015by030	Jim Knox - ES62				
29	809	025by030,045	Jim Knox - ES62				
30	810	020by030,045, 015by030redo	Jim Knox - ES62				
31	807	227371	Curtis Hill -Army				
32	800	rawbody-20121106	BillSadowski - ER33				
33	811	3flow-tube, opta_element, optb_element, cupelement	Terry Wall - ER				
34	0	MATERIAL CHANGE - CL100NB					
35	812	first inconel	Doug Wells - EM20				
36	814	thermocouple-probe-unfinished-1	Nick Case - ER21/Erin Bett				
37	0	MATERIAL CHANGE - In718 Union Carbide					
38	816	doug wells samples r1	Doug Wells - EM20				
39	818	1-piece-dmls-gradl-nozzle	Paul Gradl - ER				
40	819	1-piece-dmls-miki-prt-1-2	Paul Gradl - ER				
41	813	r0012666	David Eddleman - ER33				
42	822	54-Notch_tensile-build	derek Oneal				
43	822	54-Notch_tensile-build	Derek Oneal				
44	0	baffle test section	Lab				
45	0	MATERIAL CHANGE - CL100NB					
46	841	RS007245 - POGO1	David Eddleman - ER33				
47	841	RS007245 - POGO1	David Eddleman - ER33				
48	841	RS007245 - POGO1	David Eddleman - ER33				
49	840	med05095-1-lox-methane	Robert Polsgrove				
50	841	RS007245 - POGO1	David Eddleman - ER33				
51	0	MATERIAL CHANGE - In718 Union Carbide					
52	839	med05097_lox_methane	Robert Polsgrove				
53	854	rs007245 - POGO2	David Eddleman - ER33				
54	854	RS007245 - POGO2	David Eddleman - ER33				
55	853	valve_march4_iconel	jonathan Jones - ER50 -				
56	862	poppet, pyro	Jim Richard - ER				
57	863	VW-housing-bottom, VW-housing-top	Niki Werkheiser - ZP01				
58	0	MATERIAL CHANGE - In 625					
59	877	med04217	Darron Rice - ER34				
60	876	med04420	darron Rice - ER34				

ID	R#	Task Name	Customer	Material	Duration	Start	Finish
61	889	inj_hole_test_plate	chanceGarcia - ER32	inconel 625	2 days?	Tue 4/2/13	Wed 4/3/13
62	856	hd5_nozzle_thin	Chris Protz	inconel 625	16 days?	Wed 4/3/13	Thu 4/18/13
63	858	SLS ADO Blank_Internal Defects Built In	Doug Wells - EM20	inconel 625	2 days?	Thu 4/18/13	Fri 4/19/13
64	898	Heat Treat Development Tensile Samples_Inconel 625	doug Wells - EM20	inconel 625	5 days?	Mon 4/22/13	Fri 4/26/13
65	878	121048-001-a_injector_body	chanceGarcia - ER32	inconel 625	3 days?	Fri 4/26/13	Sun 4/28/13
66	879	121048-004-a_injector_oxid_cove	chanceGarcia - ER32	inconel 625	3 days?	Fri 4/26/13	Sun 4/28/13
67	880	121048-011-a_fuel_film_coolant	ChanceGarcia - ER32	Inconel 625	3 days?	Fri 4/26/13	Sun 4/28/13
68	0	MATERIAL CHANGE - Aluminum		Inconel 625	2 days	Mon 4/29/13	Tue 4/30/13
69	857	3d Mesh Grids	JimKnox - ES62	Aluminum	13 days	Wed 5/1/13	Mon 5/13/13
70	900	MED02289, MED02261 (Fuel Turbopump Attachment Brackets)	Nick Case - ER21/Erin Betts - ER21	Aluminum	13 days	Wed 5/1/13	Mon 5/13/13
71	0	MATERIAL CHANGE - CL100NB			1 day	Tue 5/14/13	Tue 5/14/13
72	899	Injector - (3 qty total - split into 2 builds)	Sandy Greene - ER32/Darr	Inconel 718	2 days	Wed 5/15/13	Thu 5/16/13
73	908	Injector - (3 qty total - split into 2 builds)	Sandy Greene - ER32/Darr	Inconel 718	6 days	Fri 5/17/13	Wed 5/22/13
74	907	thrusternozzle050813	Jack Chapman - ER23	Inconel 718	6 days	Fri 5/17/13	Wed 5/22/13
75	909	MOOG Valve Body with Samples	Catherine Sanders - ER33	Inconel 718	5 days	Thu 5/23/13	Mon 5/27/13
76	906	POGO Z Baffle Assembly Build 3	David Eddleman - ER33	Inconel 718	21 days	Tue 5/28/13	Mon 6/17/13
77	910	Coolant Control Valve Housing, body_ccv_inst	David Eddleman - ER33	Inconel 718	7 days	Tue 6/18/13	Mon 6/24/13
78	894	bellows	JimRichard - ER33	Inconel 718	7 days	Tue 6/18/13	Mon 6/24/13
79	918	rebuild of 908-1 injector	Sandy Greene - ER32/Darr	Inconel 718	7 days	Tue 6/18/13	Mon 6/24/13
80	920	hydrogen embrittlement samples	Erin Betts - ER32	Inconel 718	7 days	Tue 6/18/13	Mon 6/24/13
81	934	Thermal Processing Samples	Doug Wells - EM20	Inconel 718	3 days	Mon 6/24/13	Thu 6/27/13
82	892	wedge	JimRichard - ER33	Inconel 718	1 day	Thu 6/27/13	Fri 6/28/13
83	890	body.prt.15	JimRichard - ER33	Inconel 718	1.5 days	Thu 6/27/13	Fri 6/28/13
84	937	hot_gas_igniter.stp	Nick Case - ER21/Erin Bett	Inconel 718	2 days	Thu 6/27/13	Fri 6/28/13
85	883	121048-025-a_chamber_exhaust_fl	ChanceGarcia - ER32	Inconel 718	9 days	Fri 6/28/13	Sun 7/7/13
86	882	121048-023-a_chamber_front_flan	ChanceGarcia - ER32	Inconel 718	9 days	Fri 6/28/13	Sun 7/7/13
87	938	119051-021-020_chamber_tube_lin	ChanceGarcia - ER32	Inconel 718	9 days	Fri 6/28/13	Sun 7/7/13
88	881	121048-021-a_chamber_liner_form	ChanceGarcia - ER32	Inconel 718	9 days	Fri 6/28/13	Sun 7/7/13
89	940	Thermal Processing Samples - Qty 150	Doug Wells - EM20	Inconel 718	18.5 days		
90	946	Tesla	Lisa Bates - ER35	Inconel 718	1 day		
91	942	Research Build - Qty 73	Doug Wells - EM20	Inconel 718	6 days		
92	912	Gauge block	James Walker - EM20	Inconel 718	5 days		
93	947	lps01517-crossover_hsg_inst-003	Kevin Baker - ER34	Inconel 718	5 days		
94	0	MATERIAL CHANGE - In 625		Inconel 625	1 day		
95	943	hydrogen embrittlement samples - qty 90	Erin Betts - ER32	Inconel 625	7 days		
96	0	MATERIAL CHANGE		Aluminum	1 day		
97	874	4 chamber mesh	JimKnox - ES62	Aluminum	5 days		
98	914	Gauge block	James Walker - EM20	Aluminum	5 days		
99	944	hydrogen embrittlement samples - Qty 16	Erin Betts - ER32	Aluminum	5 days		
100	0	MATERIAL CHANGE - Carpenter 718		Inconel 718	2 days		
101	957	Laser Wattage Trials - Qty 18 - Group 1	Doug Wells - EM20	inconel 718	4 days		
102	960	Laser Speed Trials - Qty 18 - Group 2	Doug Wells - EM20	inconel 718	7 days		
103	961	Laser Hatch Trials - Qty 18 - Group 3	Doug Wells - EM20	inconel 718	7 days		
104	915	LOX POST TEST PIECE	Darron Rice - ER34	Inconel 718	7 days		
105	865	lps01006-001_vane	MartyCalvert - ER31	Inconel 718	7 days		
106	956	doe_orifice_build_asm	David Eddleman	Inconel 718	7 days		
107	0	Issues with Small Build Chamber Seals, etc		Inconel 718	8 days		
108	0	MATERIAL CHANGE - Union Carbide 718		Inconel 718	1 day		
109	979	NIST sample, et al	Dr. Chou - UofA	Inconel 718	3 days		
110	0	Issues with Broken Inserts		Inconel 718	9 days		
111	0	Government Shutdown			16 days		
112	962	Laser Wattage Trials - Qty 18 - Group 4	Doug Wells - EM20	inconel 718	4 days		
113	0	Dustin/Stacey DOE trials			10 days		
114	963	Laser Speed Trials - Qty 18 - Group 5	Doug Wells - EM20	inconel 718	4 days		
115	964	Laser Hatch Trials - Qty 18 - Group 6	Doug Wells - EM20	inconel 718	4 days		
116	990	Laurel Karr Gears			1 day		
117	0	Concept Laser Camera Install			12 days		

ID	R#	Task Name	Customer	Material	Duration	Start	Finish
118	0	Oxygen Sensor Failure - M2 Machine OFFLINE			7 days	Thu 11/21/13	Wed 11/27/13
119	991	Orion Screen Filter	Terry Abel	Inconel 718	5 days	Thu 11/28/13	Mon 12/2/13
120	0	Scan Line Testing			3 days	Tue 12/3/13	Thu 12/5/13
121	1004	NDE Missing Layer ADO specimens	Doug Wells - EM20	Inconel 718	3 days	Fri 12/6/13	Sun 12/8/13
122	0	ORNL parameter blocks	Stacey Bagg - EM30	Inconel 718	1 day	Mon 12/9/13	Mon 12/9/13
123	980	lps01511-h02a-pump_hsg-003	MartyCalvert - ER31	Inconel 718	17 days	Tue 12/10/13	Thu 12/26/13
124	981	lps01513-h01a-inlet_hsg-003	MartyCalvert - ER31	Inconel 718	10 days	Fri 12/27/13	Sun 1/5/14
125	0	MATERIAL CHANGE - In 625		Inconel 625	5 days	Mon 1/6/14	Fri 1/10/14
126	0	Inco625 Optimization	ADO Adv Dev Office	Inconel 625	20 days	Sat 1/11/14	Thu 1/30/14
127	0	MATERIAL CHANGE - Union Carbide 718		Inconel 718	1 day	Fri 1/31/14	Fri 1/31/14
128	982	lps01517-h01b-crossover-003	MartyCalvert - ER31	Inconel 718	5 days	Sat 2/1/14	Wed 2/5/14
129	911	15 deg compliant mounting bracket	Jonathan Jones - ER50 -	Inconel 718	5 days	Thu 2/6/14	Mon 2/10/14
130	958	scaled_55_tsc_main_body; scaled_55_tsc_nose	Victor Pritchett - EV33	Inconel 718	5 days	Tue 2/11/14	Sat 2/15/14
131	0	MAINTENANCE			5 days	Sun 2/16/14	Thu 2/20/14
132	975	heat-shield-1-3	Dave Reynolds -XP10	Inconel 718	5 days	Fri 2/21/14	Tue 2/25/14
133	1023	In625 Default Tensile Coupons	Chris Crumbly	Inconel 625	5 days	Wed 2/26/14	Sun 3/2/14
134	1026	Arcam Rakes	Bob Carter	Inconel 625	5 days	Mon 3/3/14	Fri 3/7/14
135	1024	ADO In625 2nd Batch	Chris Crumbly	Inconel 625	26 days	Sat 3/8/14	Wed 4/2/14
136	1028	ORNL 625 Test Blocks	Stacey Bagg	Inconel 625	2 days	Thu 4/3/14	Fri 4/4/14
137	1032	inlet_adapter_batch; cap	Morgan Abney	Inconel 718	18 days	Sat 4/5/14	Tue 4/22/14
138	1034	LPS02014-003-slm.stp	Darron Rice	Inconel 718	14 days	Wed 4/23/14	Tue 5/6/14
139	1039	In718 DOE Redo 030mm Layers	Doug Wells	Inconel 718	14 days	Wed 5/7/14	Tue 5/20/14
140	1040	In718 DOE Redo 045mm	Doug Wells - EM20	Inconel 718	2 days	Wed 5/21/14	Thu 5/22/14
141	1044	redo of 718 045mm DOE	Doug Wells - EM20	Inconel 718	1 day	Fri 5/23/14	Fri 5/23/14
142	1045	Redo 718 Heat treat study	Po Chen EM30	Inconel 718	24 days	Sat 5/24/14	Mon 6/16/14
143	1047	lps02004-003	Darron Rice	Inconel 718	6 days	Tue 6/17/14	Sun 6/22/14
144	1046	med06299-103	Sandy Greene - ER32/Darr	Inconel 718	14 days	Mon 6/23/14	Sun 7/6/14
145	913	POGO Z Baffle with Defects	James Walker - EM20	Inconel 718	14 days	Mon 7/7/14	Sun 7/20/14
146	0	[M1] Install			0 days	Mon 7/21/14	Mon 7/21/14
147	1049	[M1] 718 comparison run	LEO	Inconel 718	5 days	Mon 7/21/14	Fri 7/25/14
148	1050	[M2] 718 comparison run	LEO	Inconel 718	5 days	Mon 7/21/14	Fri 7/25/14
149	1038	[M1] FastValve2	Jim Richard - ER	Inconel 718	15 days	Sat 7/26/14	Sat 8/9/14
150	0	[M2] MATERIAL CHANGE - Ti-6-4		Ti-6Al-4V	5 days	Sat 7/26/14	Wed 7/30/14
151	1051	[M2] ADO Ti-64 DOE1	Chris Crumbly	Ti-6Al-4V	25 days	Thu 7/31/14	Sun 8/24/14
152	1042	[M2] med06199-001	Tim Kibbey	Ti-6Al-4V	10 days	Mon 8/25/14	Wed 9/3/14

Red = contaminated

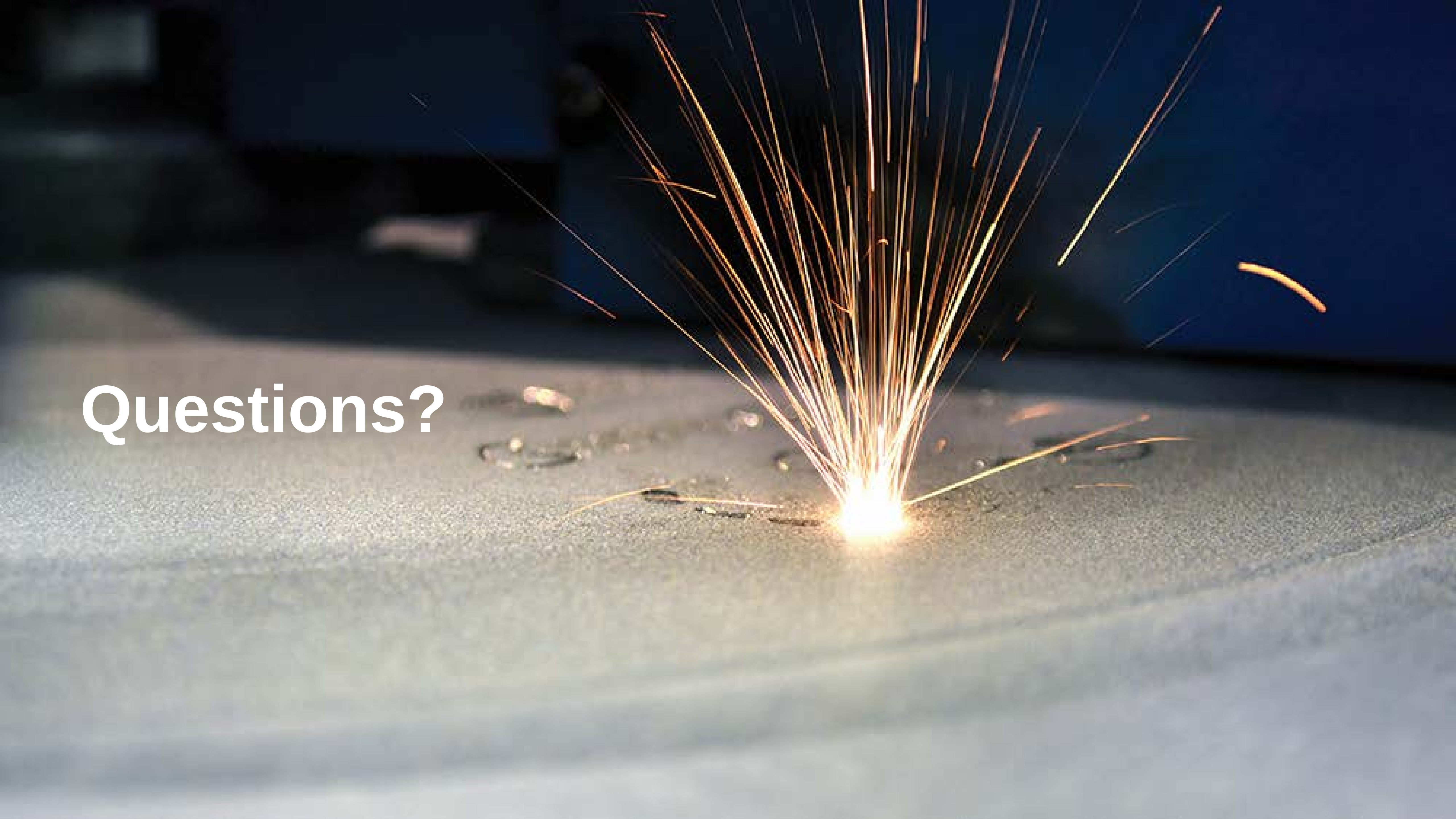
Green = not-contaminated

Contamination was more wide-spread than originally believed.

Lessons Learned:

- Create a schema early on in the development effort to capture necessary data
- Standardization helps ensure proper processing steps are taken and traceability of components

Questions?



Presenter Bio

Christopher Roberts, NASA MSFC

Christopher Roberts is a materials engineer at NASA Marshall Space Flight Center. He received his B.S. in Mechanical Engineering from Auburn University (2014) and his M.S. and Ph.D. in Materials Science and Engineering from the University of Texas at Austin (2016 and 2018, respectively). His graduate work focused on developing materials and processes for Selective Laser Melting (SLM) of traditionally hard-to-process material systems. For the past year and a half, he has worked closely with the In-Space Manufacturing (ISM) team at MSFC to develop additive manufacturing technology demonstrators and to monitor SBIR contracts addressing various challenges associated with manufacturing in space. Furthermore, he is currently working with a number of projects on how to effectively develop and implement additive manufacturing standards and controls.