National Aeronautics and Space Administration

Ntidrodium Material Property Suite (MPS)

A Fictitious Example with Real World Application

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First Some Context: NASA STD 6030

NASA-STD-6030, titled “Additive Manufacturing Requirements for Spaceflight Systems”, is NASA’s set of requirements for using additive parts in a spaceflight application

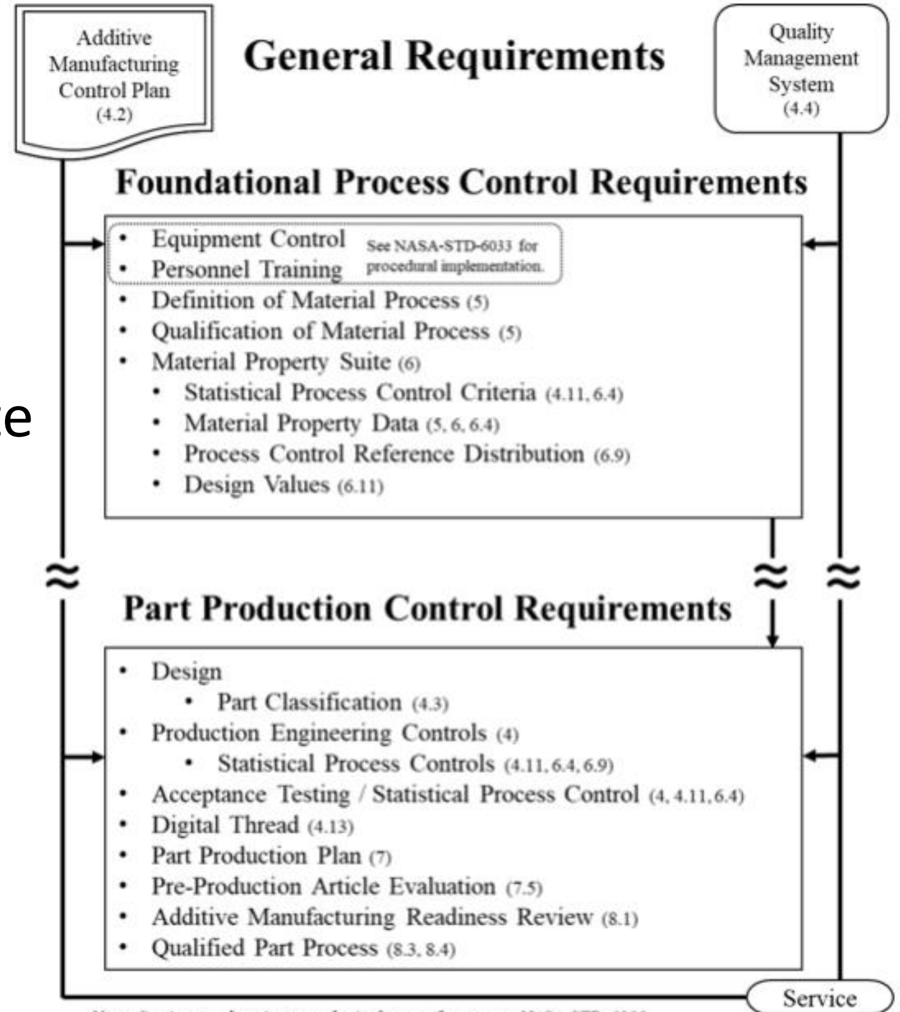
- 6030 is not intended for prototyping, instead the focus is making reliable parts for critical applications
  - If you are in the move fast and break things mode, this standard does not align with that mentality
- 6030’s focus is on using additive manufacture (AM) intentionally with communication and context. That is why the standard focuses Foundational Process Controls and Part Production Controls.

NASA STD 6030 and You: Main Principles

- Foundational Process Controls: How you
  - Define your process
  - Characterize your process
  - Monitor your process
  - Use the process for a design

Role of the Materials Property Suite

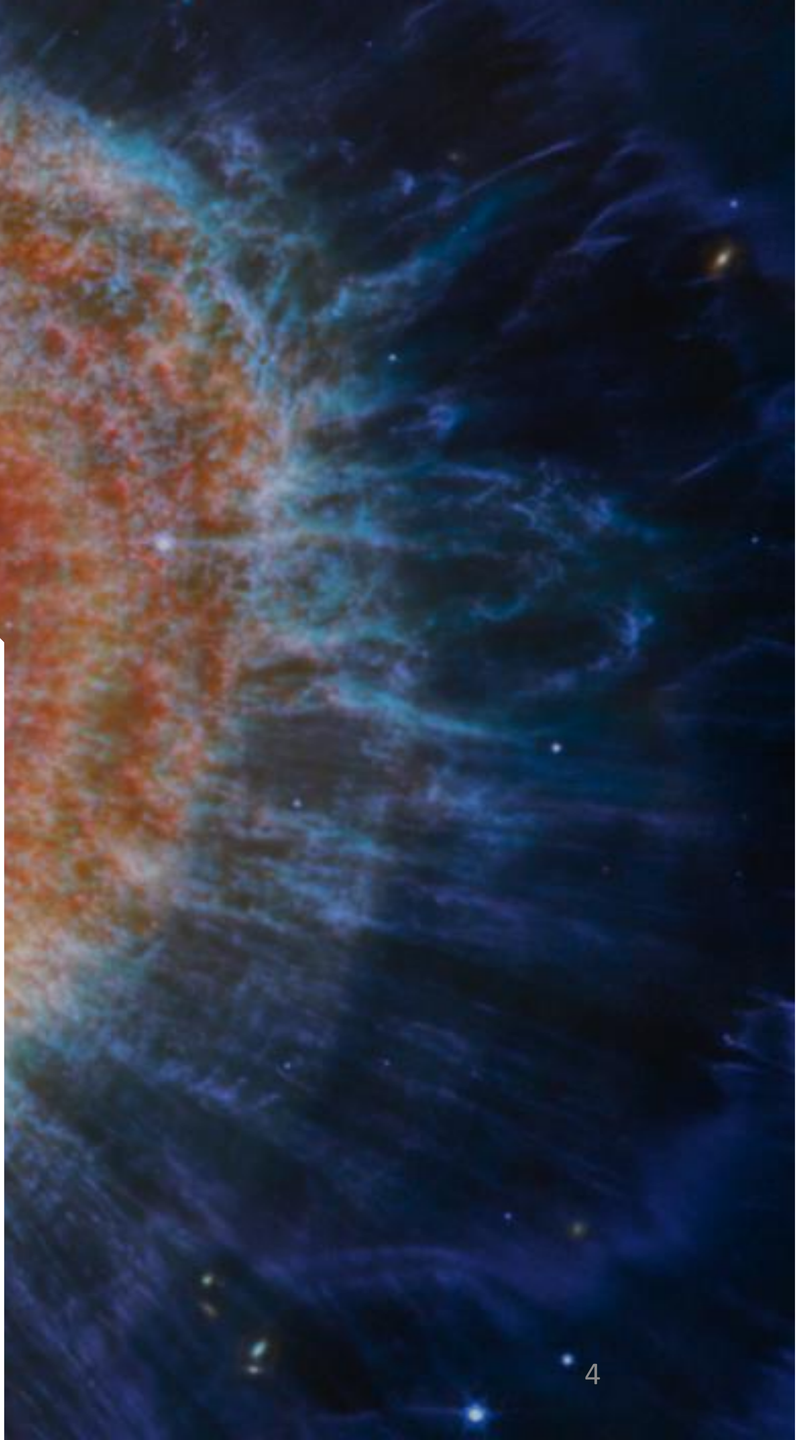
- Part Production Controls: How you
  - Will document additives benefits for your application
  - Will be making your part
  - Will qualify your part
  - Will ensure part success



Note: Section numbers in parentheticals are references to NASA-STD-6030 section numbers, unless stated otherwise

The Materials Property Suite

A Comprehensive Guide to an Additive Material



What is a Materials Property Suite?

- NASA Standard 6030 has descriptive requirements for properties, instead of prescriptive limits. This means that the existent state of the material must be documented.
- A Material Property Suite contains the information on the state of the material and cites the processes to produce
    - Covers mechanical and physical properties, alongside microstructure
    - Establishes the reference distribution that must be matched by later AM coupons to be under this MPS
- This example MPS is a single document, but any system that integrates the database of properties and microstructure information to establish design values can work

Why would we need a Materials Property Suite?

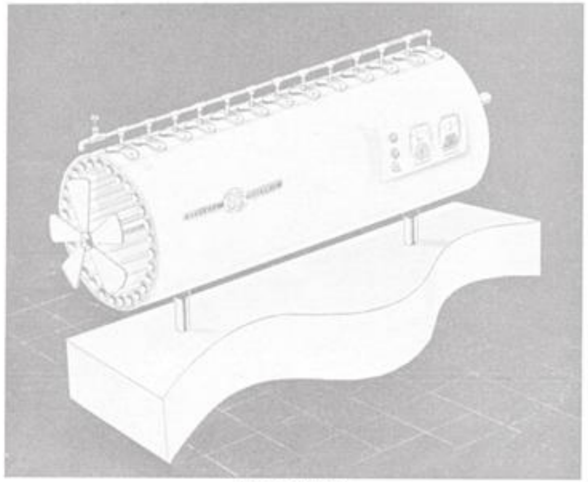
- Collects Necessary Information
  - A properly constructed MPS collects the information that designers need to know on the material
  - Clearly references the processes that produce this material
- Advertise Capabilities
  - A MPS can be sent to projects or customers to describe the material and inform their designers of properties
  - Demonstrates Quality, Documentation, and Reliable Properties in one place
- Creates Trust Parity
  - The testing required to be compiled in an MPS are equivalent to those expected from a foundry for conventional part. This can address some of the skepticism around additive part reliability

Why create example documents?

- Standardize Expectations
  - 6030 is intentionally flexible in its requirements but this can make it difficult to parse what a document meeting those requirements would look like
    - Creating an example which meets these requirements gives a starting point
- Communicate with Additive Fabricators
  - NASA-STD-6030, with 190 pages and 115 shall statements can be an intimating standard. Seeing an example can help overcome the initial hurdle
  - Demonstrate reasonable tailoring and limitations
- Coordinate NASA Internal Efforts
  - Provides an example for NASA personnel of what 6030 requires

Nitidrodium

Sometimes the best example is one that does not exist



(Photo 2904401)
Fig. 1. Turboencabulator

THIS PUBLICATION CONTAINS INFORMATION ON THE FOLLOWING

FUNCTION

To **measure** inverse reactive current in unilateral phase detractors with display of percent realization.

OPERATION

Based on the principle of power generation by the modial interaction of magnetoreluctance and capacitive directance, the Turboencabulator negates the relative motion of conventional conductors and fluxes. It consists of a baseplate of prefabulated Amulite, surmounted by a malleable logarithmic casing in such a way that the two main spurving bearings are aligned with the pentametric fan.

Six gyro-controlled antigravic marzelvanes are attached to the ambifacient wane shafts to prevent internal precession. Along the top, adjacent to the panandermic semi-boloid stator slots, are forty-seven manestically spaced grouting brushes, insulated with Glyptal-impregnated, cyanoethylated kraft paper bushings. Each one of these feeds into the rotor slip-stream, via the non-reversible

* Included Qty. 6 NO-BLO‡ fuses.
† Includes Magnaglas circuit breaker with polykrapolene-coated contacts rated 75A Wolfram.
‡ Reg. T.M. Little Gem Fuse Blower Corp.

ACCESSORIES

1. 8 ounces 5 per cent Tetraethyliodohexamine with 0.01N Halogen tracer solution.
2. Interelectrode diffusion integrator.
3. Noninductive-wound inverse conductance control in little black box.
4. Analog to digital converter with reflected levorotatory BCD output (binary-coded decimal ie; 7, 4, 2, 1).
5. Quasistatic regeneration oscillator with output conductance of 17.8 millimhos.

APPLICATION

Measuring Inverse Reactive Current—CAUTION: Because of the replenerative flow characteristics of positive ions in unilateral phase detractors, the use of the quasistatic regeneration oscillator is recommended if Turboencabulator is used in explosive atmospheres.

may be obtained from:

Torricelli Barometer Works, Ltd.
Toroidal Turboencabulator Dept. (TTD-3)
London W.C. 1, England.

In Canada address request to:

Turboencabulateurs
Canadien-Francais Ltee.
468 Jean de Quen, Quebec 10, P.Q.

Reference Texts

1. Zeitschrift fur Physik
Der Zerfall von Dunge LBM-1
H. Sturtzkampflieger, Berlin
2. Svenska Teckniska Skatologika Larovarken
Dagblad 121—G. Petterson & W. Johannson, Stockholm
3. Journaux de l'Academie Francaise
Numero 606B
T. L'Ouverture, Paris
4. Szkola Polska
Turboencabulatorskiego
Ogloszenie 1411-7
Bogumiel Wroblyski, Warszawa.
5. Texas Inst. of Turboencabulation
AITE Bull. 312-52, J. J. Fleck, Dallas.

SPECIFICATIONS

Accuracy: ±1 per cent of point
Repeatability: ±¼ per cent
Drift: less than 3 ft²-hrs/mo
Maintenance Required: Bimonthly treatment of Meter covers with Shure Stat.
Ratings (Standard): None
Ratings (Optional): All
Input Power: Volts-120/240/480/550 a-c
Amps—10/5/2.5/2.2 A
Watts—1200 W
Wave Shape—Sinusoidal
Cosinusoidal, Tangential or Pipusoidal.

Operating Environment:
Temperature 32F to 150F (0C to 66C)
Max Magnetic Field: 15 Mendelsohns (1 Mendelsohn = 32.6 Statoersteds)

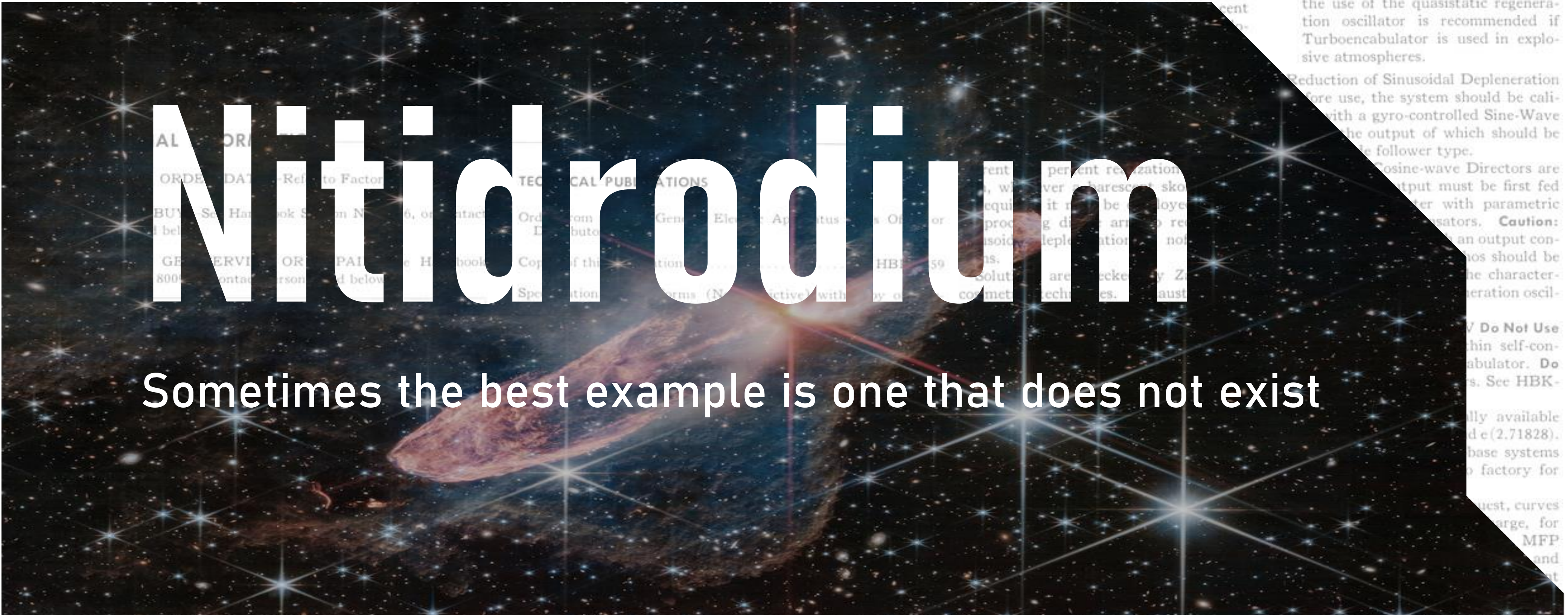
Case:
Material: Amulite; Tremie-pipes are of Crapaloy—(tungsten cowhide)
Weight: Net 134 lbs.; Ship 213 lbs.

DIMENSION DRAWINGS

On delivery.

EXTERNAL WIRING

On delivery.

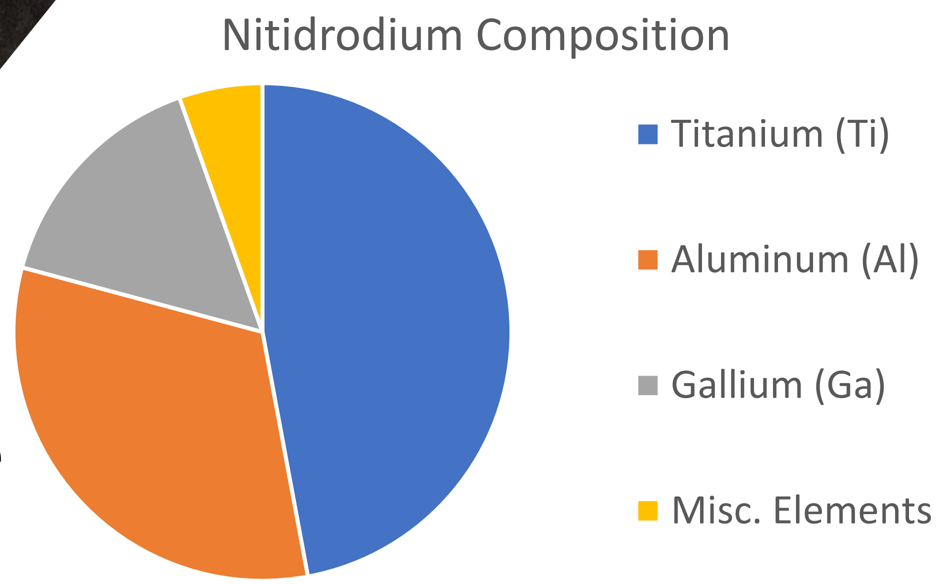


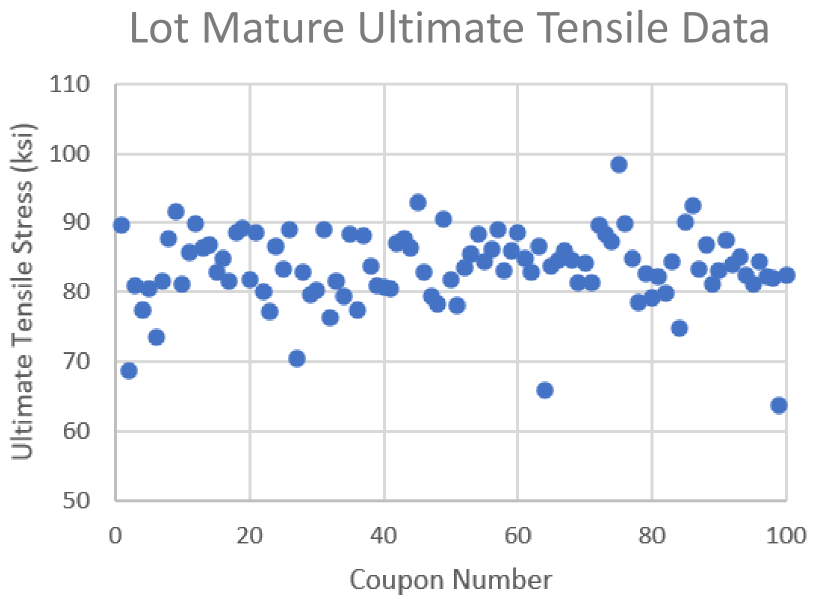
Why use fictional material?

- Ease of Disseminating Information
  - A fictitious material is not subject to export control limitations
  - Do not need to procure information from real studies or get permission to replicate data
- Reduces misunderstandings
  - Having a clearly unstable chemistry, unrealistic heat treatment parameters, and unlikely property ranges makes it clear to readers joining at any point that the material is not real
  - If the document is used as a template the unusual numbers make spotting non-updated figures easy
  - Still has actual numbers to show expected formatting and data spread

Generating Ntidrodium Data

- Chemical and Physical properties are not subject to later statistics, so reasonable approximates could be chosen arbitrarily
- Tensile mechanical properties undergo more statistical examination, so a dedicated effort was made to produce realistic variation in the data
  - A lot mature data set with 100 tensile coupons was generated
  - Prior to my involvement with this effort Zhaofeng C. Huang created a tool for simulating AM data, which utilizes a range of "build parameter sets" and "build profiles" to generate data spread we'd expect in additive properties





Materials Property Suite Building Blocks

Putting the pieces together, and what pieces you need

What a Materials Property Suite Requires

- Baseline Documentation
  - Title Page, Scope, Limitations, Material Designation, Relevant Specifications, References
- Processing References
  - Feedstock Composition, Registered Qualified Material Processes (QMP) and Sub-QMPs, Heat Treatment
- Properties
  - Chemical and Physical: Build Chemistry, Microstructure, Thermal Properties
  - Mechanical Properties: Tensile, Young’s Modulus, Elongation, Fracture Toughness, Elevated Temperature Tensile, Fatigue
- Statistical Process Control
  - Define Reference Distribution, Define Control Limits, Control Charts

Making a Teachable Example

Just because an example document meets requirements does not mean it is useful for people looking to create their own MPS. Extra care was taken in the following areas to improve utility.

- Context- Blue Boxes contain discussion on why particular choices were made in the document, as well as the methodology for less transparent sections
- Clarity- Whenever the document differs from the expected information in a MPS it is noted and explained in commentary boxes
- Conciseness- The formatting was kept slim and extraneous commentary to a minimum

...ge

...0.25 hrs

... Vacuum

...pecial Considerations

...1.8.1. **Fabrication Considerations: Heat Treatment**
At elevated temperatures the alpha phase of this metal can oxidize and embrittle, reducing fracture toughness significantly. Heat treatment atmospheres should be kept below 150 ppm Oxygen to produce material in keeping with this MPS

> **Discussion: Fabrication Considerations**- While the QMP cited in Section 1.4 has detailed fabrication instruction, this fabrication consideration subsection provides a space to cover any additional concerns when working with the material. If the material is prone to warping or hot cracking, for example, then it may be worthwhile to mention it here. This section is not intended to be a full process description; so, the MPS should only highlight particularly important points, leaving the rest in the QMP.

2. Physical and Chemical Properties
Testing details and coupon geometries can be found in GSFC D-1234569 "Design Allowables Generation Guidelines for Laser Powder Bed Fusion Additive Manufacturing", latest release

2.1. Chemical Properties

2.1.1. [Table] Printed Composition

2.1.2. Microstructure

2.1.2.1. [Figure] As Built

2.1.2.2. [Figure] HIPed

Figure 2.1.2.3 Solution Treated and Aged Microstructure (c)

> **Discussion: Image Source**- As this material is fictional, the micrographs seen above are of a Inconel Alloy 718, provided by Colton Katsarelis of Marshall Space Flight Center.
>
> While the above micrographs are not of the fictional alloy discussed in this document, they are captured during a similar sequence of post processing. Microstructure will vary wildly depending on the material, so a similar procession should not be assumed. While discussions of the requirements for the microstructure are held in the QMP, annotations may be helpful in cases where there are features of the microstructure that need to be explained.

Baseline Documentation

- This Document is formatted as a NASA internally created MPS
  - Primarily as this allows the "in universe" document preparers to be the same as the example writers
  - Minimal edits could make this formatting suitable for any company
- All MPSs describe material produced to a set quality class, which needs to be noted in the document
  - Any geometric limitations for the parts the MPS is intended to cover also must noted

Document ID: XYZ

Laser Powder Bed Fusion Nitidrodium Material Property Suite (MPS) For Class A Applications

Revision C

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Effective xx/xx/2023

Paper copies of this document may not be current and should not be relied on for official purposes. The current version can be found on the NASA Technical Report's Server (NTRS).

1.1. Scope

This document will detail a Class A Material Property Suite (MPS) for Nitidroium produced using laser powder bed fusion.

1.2. Limitations

This MPS is not applicable for thin-walled structures below 0.100" in wide in the build plane, or thick-walled structures over 5.000" in the build plane. This MPS is limited to single laser powder bed fusion machine that use a recoater blade to level the build plane

1.3.Designations

Nitidrodium31, NITDRO-Al31, NITIAL31

1.4.Specifications

GSFC D-1234567 Rev.C - TurboEncaltech Nitidrodium Feedstock Powder Specification for Laser Powder Bed Fusion Additive Manufacturing

GSFC D-1234568 Rev. C "Heat Treatment for Nitidrodium Additively Manufactured QCI Parts".

GSFC D-1234569 Rev.C "Additive Manufacturing Center Qualified Material Process Record Nitidrodium"

Processing References

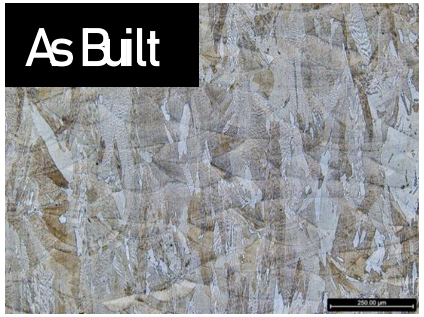
- A MPS is a description of the use state of the material, thus information on the process for producing it is focused on in Qualified Material Processes
  - All that is required is that QMPs (which have properties in family with the reference distribution) be listed with document numbers
  - Other process documents like heat treatment and feed stock composition are treated similarly
- This example MPS document has extracted some information in these reference documents to provide a more complete view of the material, which can be very valuable if permitted

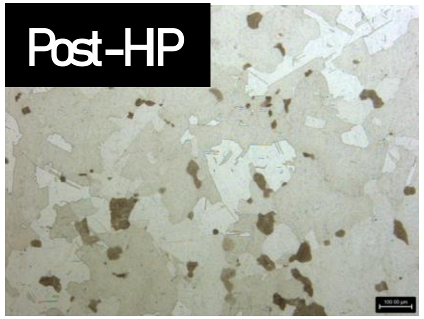
Chemical and Physical Properties

- The post-printed composition was based on the feedstock composition with some loss of lighter elements and minor random variation, as expected in a laser powder bed print
  - Most physical properties were values in the expected range for this composition
- The microstructure images were actual micrographs but are stripped of context to function as examples of the fictious material

Table 2.1.1. Typical Printed Composition

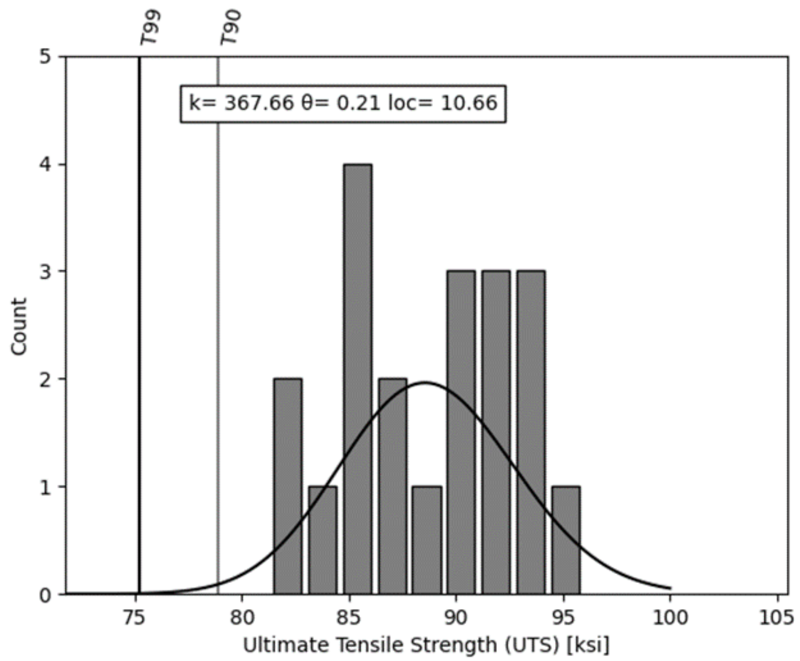
Element	Measured wt.%			
	Build 1	Build 4	Build 9	Average
Titanium (Ti)	51.0	49.2	49.6	49.9
Beryllium (Be)	0.31	0.42	0.53	0.42
Nitrogen (N)	1.00	0.98	1.01	1.00
Florine (F)	0.20	0.05	0.10	0.12
Aluminum (Al)	30.5	31.2	30.9	30.9
Iron (Fe)	0.04	0.09	0.12	0.08
Gallium (Ga)	14.4	15.0	14.8	14.7
Silver (Ag)	2.00	2.20	2.10	2.10
Indium (In)	0.50	0.53	0.54	0.52
Tin	<0.01	0.11	0.06	0.06
Other Elements, Each	0.04	0.02	0.06	0.04
Other Elements, Total	0.18	0.20	0.21	0.20





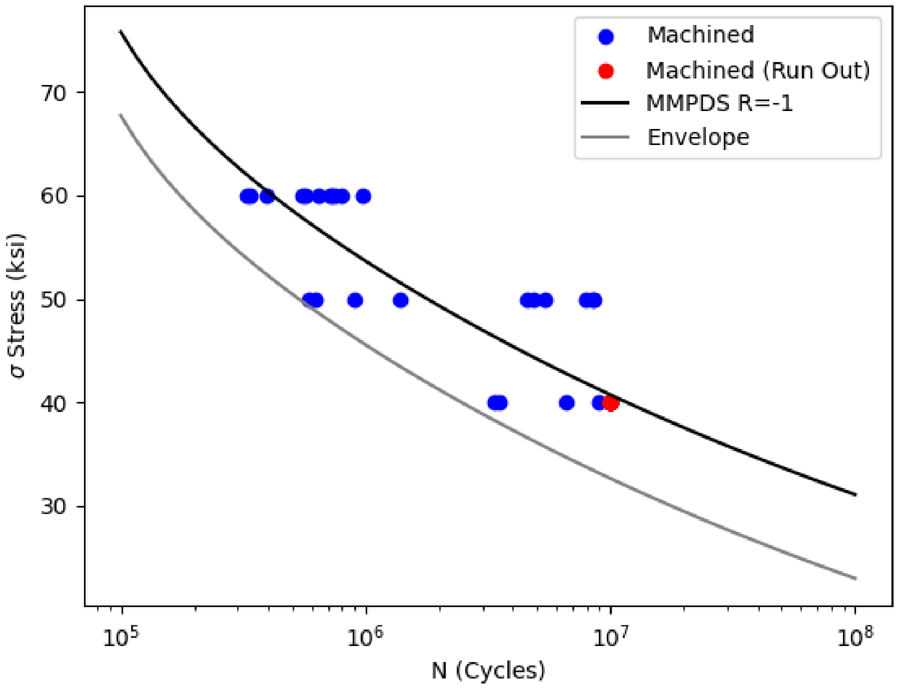
Mechanical Properties: Tensile Properties

- A majority of the Mechanical Properties Data is the tensile data generated to demonstrate statistical process control. With some simple statistics you can get plots and table values for each property.
  - Ultimate Tensile Strength, Yield Strength and Elongation are all necessary metrics to track
  - Reduction of Area was also analyzed in this MPS, primarily as a diagnostic metric
  - The distributions were described as generalized gamma distributions as they are flexible and fit closely for each property



Additional Mechanical Properties

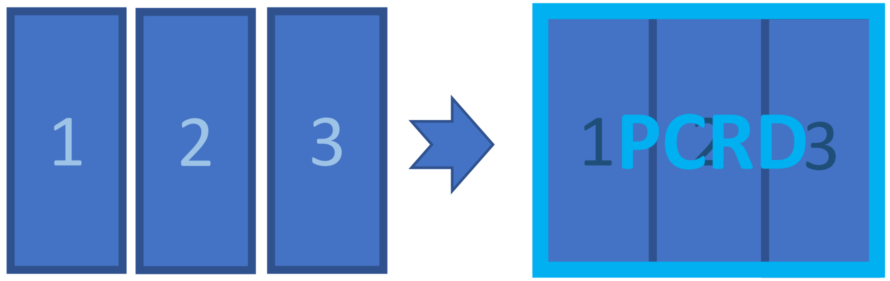
- The remaining mechanical properties did not undergo as extensive statistical analysis, so were generated with a less extensive process
  - Unplotted properties like the Young's Modulus and Ultimate Shear were assigned reasonable values in a similar manner to the chemical and physical properties
- The Fatigue plot was more detailed than required make an easier to follow plot
  - 6030 only requires 10 data points for a class A QMP the additional data points are to help compute the data envelope

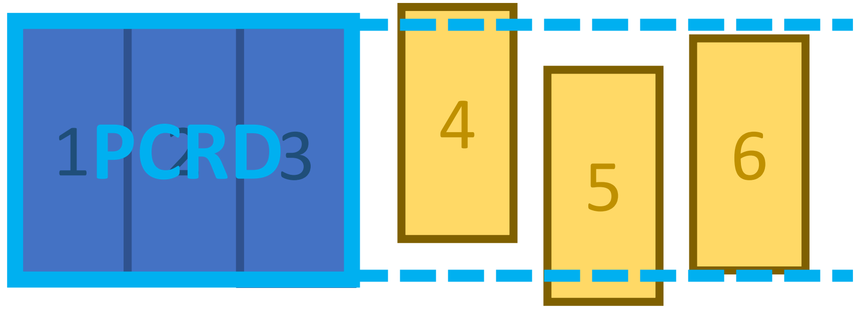


Statistical Process Control: Process Control Reference Distribution (PCRD)

- Statistical Process Control (SPC) functions by taking setting statistical control limits which later witness coupons can be evaluated against to make sure the process remains in family
- To get these limits a portion of the builds are designated as the Process Control Reference Distribution (PCRD)
  - In this case the first 3 builds were selected which contain a total of 32 coupons, from two powder lots

Consistent Builds





The PCRD is used to establish limits for following builds

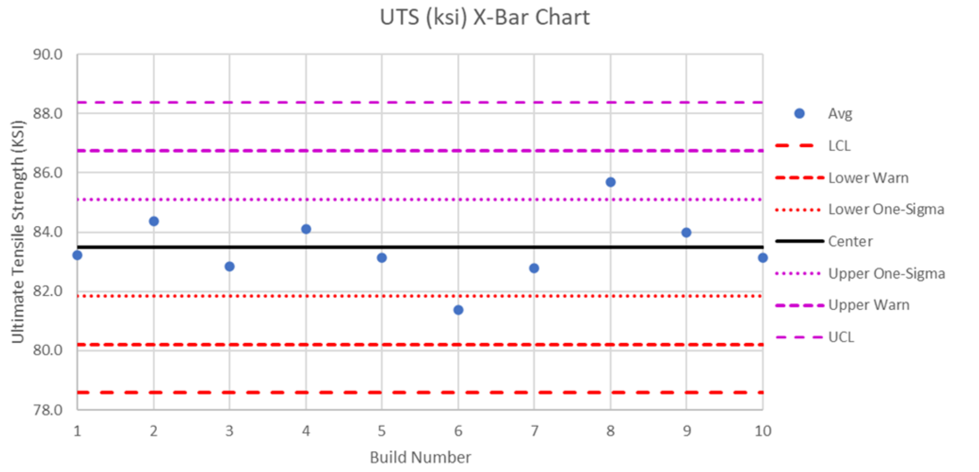
Statistical Process Control: Utilizing a PCRD

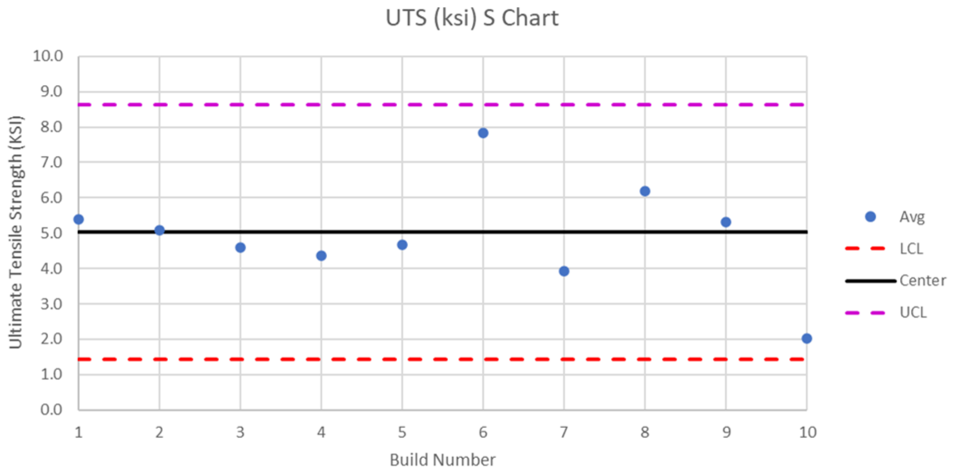
- Before limits are derived from the Process Control Reference Distribution you need to calculate the set's basic statistics
  - Mean, Covariance (COV), Standard Deviation, T90, and T99 were calculated for all 4 tracked tensile properties. Though only the Mean and Standard deviation were used to define control limits.
- The PCRD is intended to be expanded as more data is found to be in family
  - To explain the process of expanding the PCRD section 4.4 of the MPS justifies the expansion but that reasoning wouldn't normally be in an MPS

Builds	Update Frequency
1-10	5
11-50	10
51-100	20
101-500	50
501-1000	100
1000	250

Statistical Process Control: Control Charts

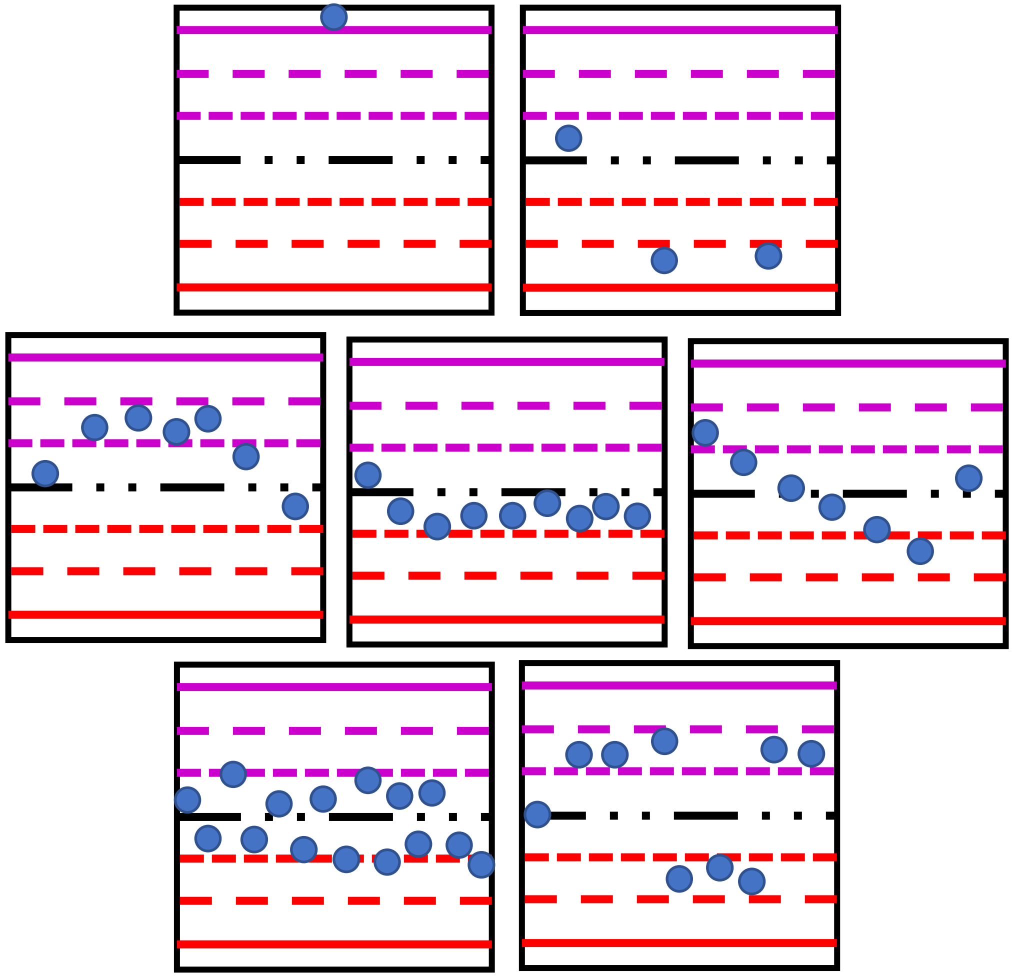
- This example document follows the ASTM E2587 SPC procedure, warning limits and control limits can be established
- Each property has two control charts, the $\bar{x}$ chart tracks the mean of the property per build and the S chart which tracks the standard deviation per build
  - The Upper and Lower Control Limits are the line past which there is immediately assumed to be process shift
  - The Warning and One Sigma Limits only demonstrate shift if there is clustering past them





Statistical Process Control: Using Control Charts

- As the control charts are intended to capture process drift, they track properties on a build-by-build basis and not per coupon
- This example uses Western rules as defined in ASTM E2587, which has seven different conditions for detecting process shift.
  - Use of these particular rules or standard is not required, just some usage of SPC



Final Thoughts

We have a functional MPS, where do we go now?

"One Document" not "The Document"

- This document has formatting based the design of some JPL internal documentation, which also featured small sections for each property, with tables and figures held to the end. This formatting is not standard or even preferred within NASA.
- The ordering, naming, and distribution of sections does not need to match what this document has. The information is what is required, not any particular way of displaying it.
  - As discussed earlier even formatting an MPS as a single document will not be the right fit for every application
- Even the properties covered in this example MPS are not universal. For materials intended for different applications, or produced in different processes, it may be necessary to track coefficient of thermal expansion, the change in properties along an alloy gradient, or thermal properties in greater detail.

Future Work

- To demonstrate more of the range of formats that a Materials Property Suite can take, alternately formatted versions are planned
- There were sections of this MPS that would normally be expected of a Class A build but weren't filled out with fake data in this example such as thermally elevated mechanical properties and fracture toughness. Additional data should be generated for these area to provide a more complete example.
- The process of creating this MPS, and the discussions arising from it have highlighted points where NASA STD-6030 need additional clarity. Revisions are upcoming for this document, so these points should be kept in mind.

Conclusions

- A Materials Property Suite is a NASA-STD-6030 required document that describes the state of an additive material
- Using a fictitious alloy like Nitidrodium allows for a controlled, clear, sharable example
- Establishing the allowable distribution for a given material is a primary role of the MPS
- An MPS does not need to follow a set format, but having an example gives an entry point for unfamiliar users

Any Questions?

MATERIALS ENGINEERING
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Thank you for your attention!

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