National Aeronautics and Space Administration

Framework for Additive Manufacturing Material Readiness Levels in Aerospace Applications

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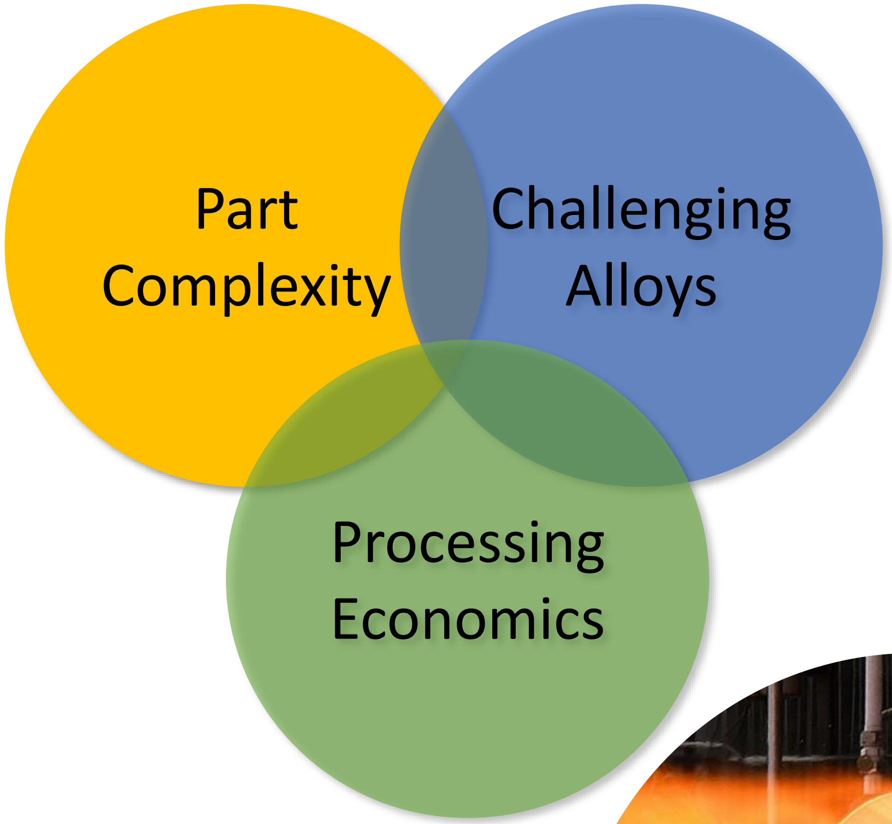
I created a new alloy, *and* I want to build critical AM components ***and*** fly them on your rocket…

The Case for Additive Manufacturing in Propulsion

- Metal Additive Manufacturing (AM) can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
  - Lead times reduced by 2-10x
  - Cost reduced by more than 50%
- Complexity is inherent in liquid rocket engines and AM provides new design and performance opportunities.
- Materials that are difficult to process using traditional techniques, long-lead, or not previously possible are now accessible using metal additive manufacturing.

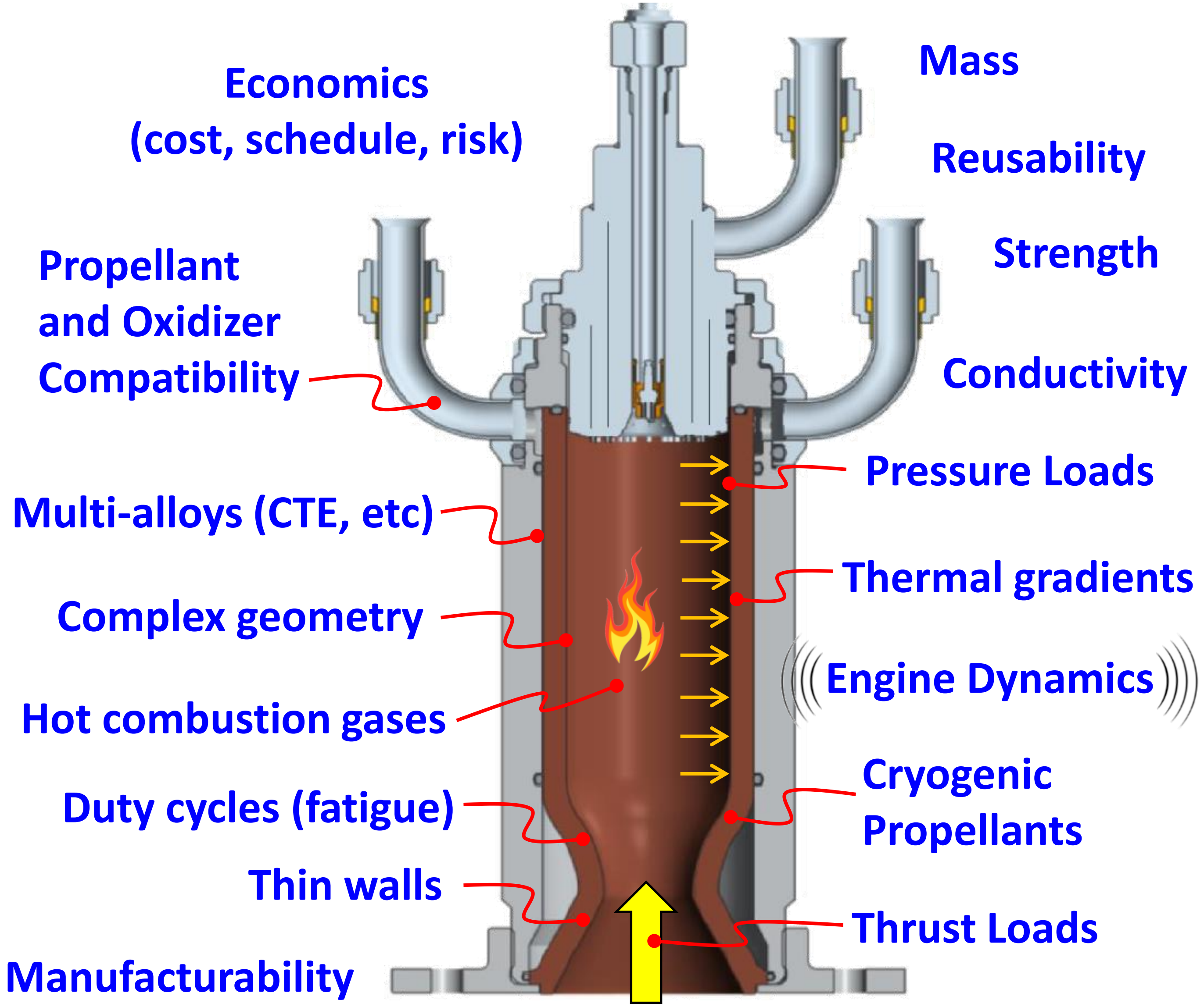


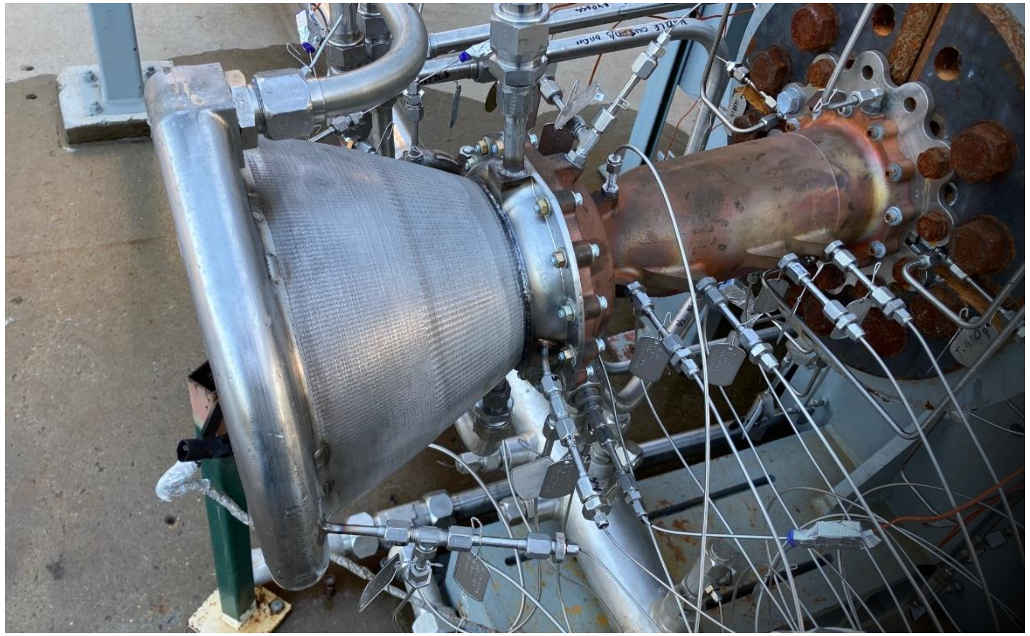
Applications Drives Materials and Materials Drive Performance

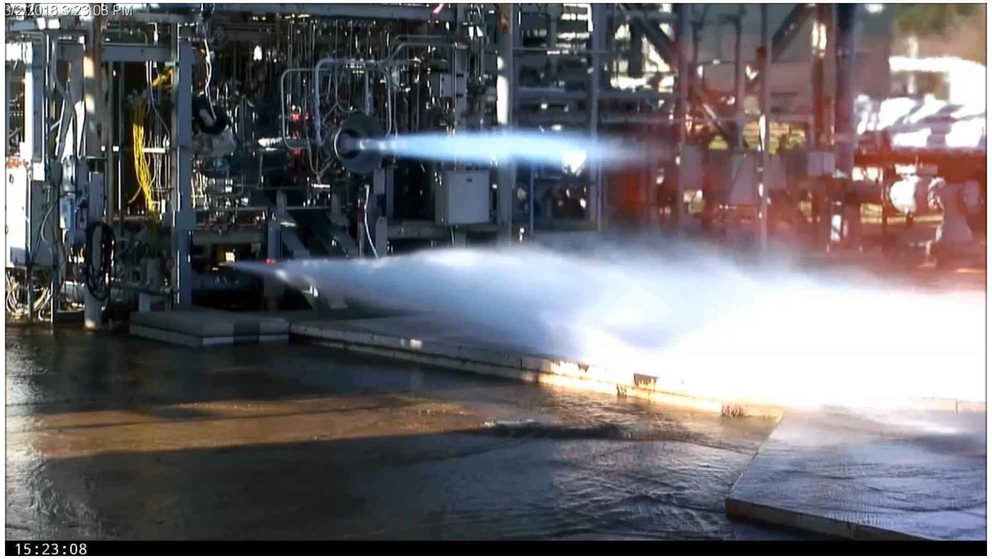
- Rocket engine components operate in extreme environments.
  - High pressure, high heat flux, high thermal gradients, long duty cycles, stress rupture (creep), oxidation.
- AM has played a pivotal role in component development and production, but materials are still based on heritage metal alloys.
- New alloys using unique advantages of AM processing can provide a step change in properties to allow for higher performance.
- Rocket engine development and vehicle architectures are pushing for high performance resulting in higher heat loads, longer durations, reusability.
- Novel materials have advanced in the last 10 years.

There is a need to advance and infuse metal alloys using additive manufacturing processes to enable higher performance.

Example: Combustion Chamber Material Considerations



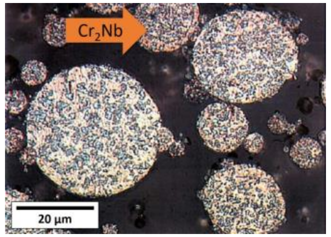




Maturity of Metal Additive Manufacturing for Space Applications

Case Study and Timeline of GRCop-42

1987

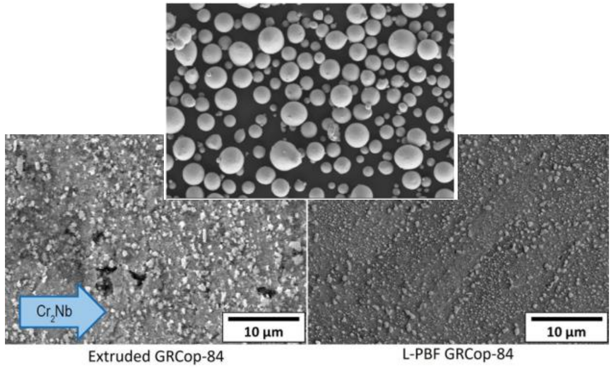


GRCop Developed

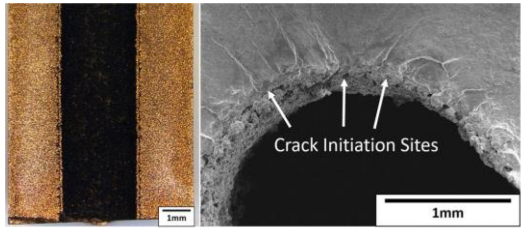
1990s

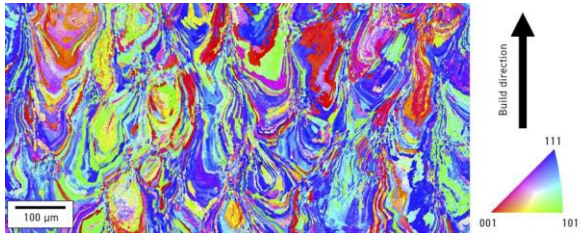
2000

2012



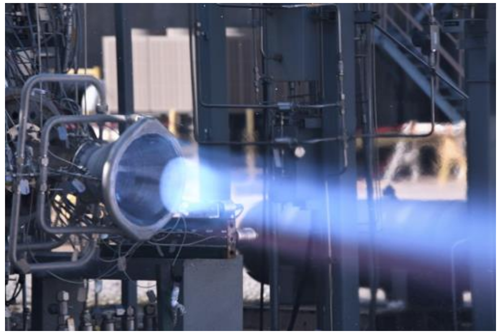
2015





2018

2019

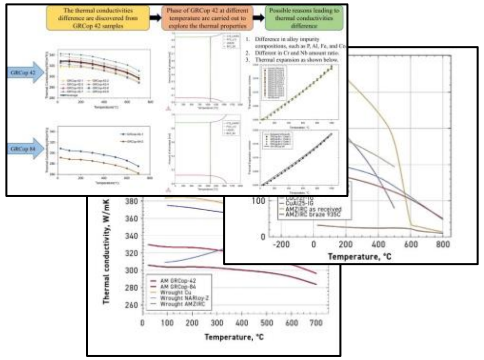


2020

2021

2023

2024



2025

What is the goal of our AM maturity model and this talk?

- Start a conversation on common maturity of new *metal* AM alloys.
  - This is not a qualification presentation but will have some flavors that seem familiar.
- Different disciplines have different perspectives.
- Pre-qualification – We talk a lot about qualification and certification but is a material even ready start the process?
- Most organizations have likely thought about or has a process for how materials are matured… or have you?
- High alloy maturity ≠ Qualified material and process.
- We can likely agree that certain alloys have high maturity… why?
  - Ti6Al4V, AlSi10Mg, Stainless 316L, CoCr, Inconel 718, Inconel 625.
  - Do we "accept" them based on familiarity with the wrought version?
  - Do we accept that a lot of AM data has been generated over time?
  - A new process means a new material.

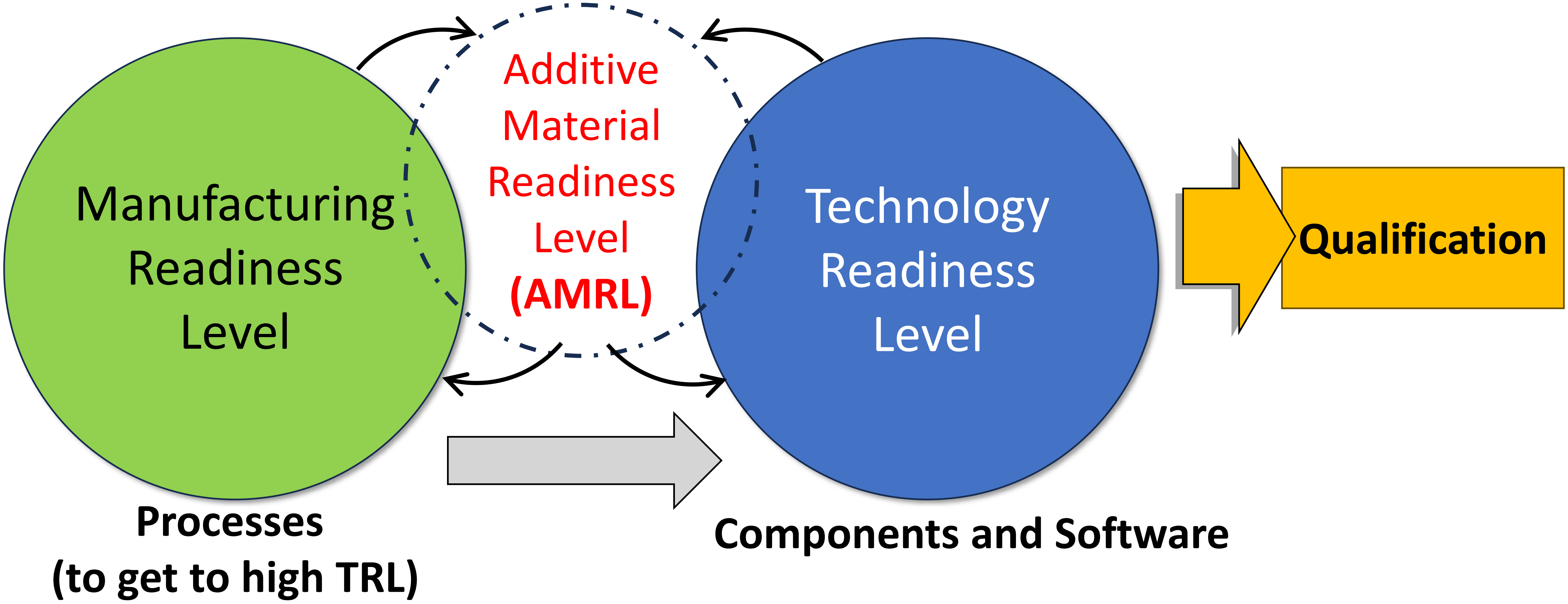
What rigor is required to properly mature an AM alloy?

Considerations for New Alloy Development

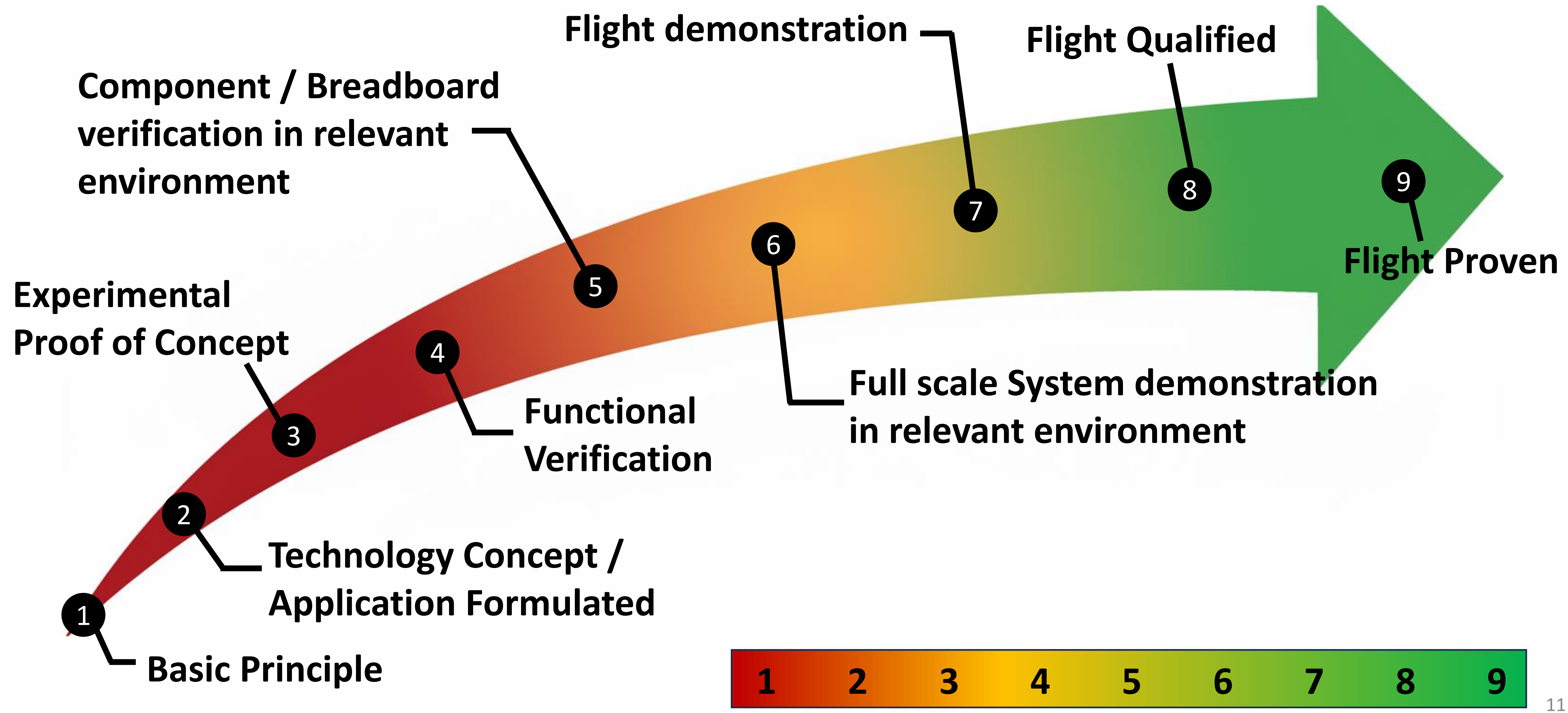
- **Business Case and Need**
  - Is the problem significant enough to justify funding a new alloy?
  - Does the end user have a strong case and commitment to mature it?
- **Fit for Additive Manufacturing**
  - Is AM the correct solution?
  - Are existing materials viable, or is a new alloy truly required?
- **Risk and Supply Chain**
  - How risky is the development for both application and supply chain?
  - Who carries the burden of alloy maturation?
- **Maturation Pathway**
  - Development must be robust and repeatable, not ad hoc.
  - Steps for maturation and risk mitigation should be clearly defined.
  - Steps can be tailored to application and requirements.
- **Industry and Regulatory Alignment**
  - Use of existing industry best practices (modeling, feedstock, mechanical testing standards)
  - Goal is to transition to a regulatory environment.
  - Data developed through AMRL maturity can be incorporated into qualification

How do we determine material maturity?

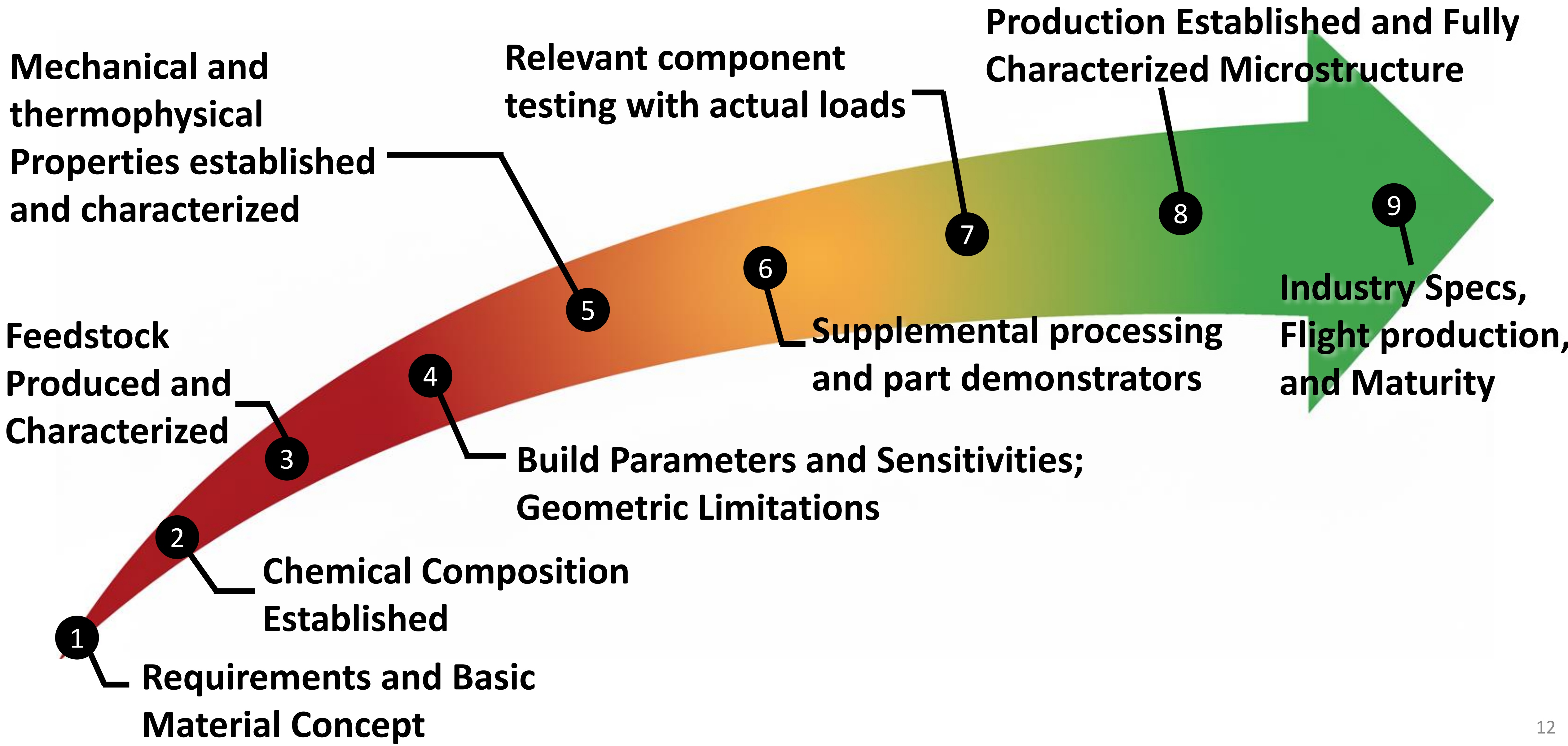
Material is an input to the process but also an output



Technology Readiness Levels



Additive Material Readiness Levels



AM Material Readiness

Basic Research

Prove Feasibility

Technology Development

Technology Demonstration

Infusion and Operation

AM Readiness Level	Attributes
1	Application Requirements + Basic Concept of Material
2	Chemical Composition Established through detailed modeling or feasibility through initial feasibility of powder and AM parameters
3	Feedstock produced and characterized
4	Parameters and sensitivities established with mature feedstock and Geometric Limitations
5	Mechanical and Thermophysical Properties Developed
6	Supplemental Processing and Part Demonstrators
7	Component testing in relevant environment with actual operational loads
8	Production Established – Fully characterized Microstructure (Repeatability and Reproducibility)
9	Flight Production and Maturity

AM Material Readiness Comparison to TRL and MRL

AM Material Readiness Level	Attributes	TRL Comparison	MRL Comparison
1	Application Requirements + Basic Concept of Material	Basic principles observed and reported	Basic manufacturing implications identified
2	Chemical Composition Established through detailed modeling or feasibility through initial feasibility of powder and AM parameters	Technology concept and/or application formulated	Manufacturing concepts identified
3	Feedstock produced and characterized	Analytical and experimental critical function and/or characteristic proof of concept	Manufacturing proof of concept developed
4	Parameters and sensitivities established with mature feedstock and Geometric Limitations	Component and/or breadboard validation in laboratory environment	Capability to produce technology in a lab environment
5	Mechanical and Thermophysical Properties Developed	Component and/or breadboard validation in relevant environment	Capability to produce prototype components in production relevant environment
6	Supplemental Processing and Part Demonstrators	System/subsystem model or prototype demonstration in a relevant environment	Capability to produce prototype system or subsystem in production relevant environment
7	Component testing in relevant environment with actual operational loads	System prototype demonstration in application environment	Capability to produce systems, subsystems, or components in production representattive environment
8	Production Established – Fully characterized Microstructure (Repeatability and Reproducibility)	Actual system completed and flight qualified through test and demonstration	Pilot line capability demonstrated begin low-rate production
9	Flight Production and Maturity	Actual system flight proven through successful operation	Low-rate production demonstrated

AM Material Readiness

AM Readiness Level	Attributes	Stakeholders
1	Application Requirements + Basic Concept of Material	Material Scientist, Requirements from Design Engr
2	Chemical Composition Established through detailed modeling or feasibility through initial feasibility of powder and AM parameters	Material Scientist, Material Engineer, **Manufacturing Engineer**
3	Feedstock produced and characterized	Material Scientist, Material Engineer, Manufacturing Engineer, **Industry**
4	Parameters and sensitivities established with mature feedstock and Geometric Limitations	Material Engineer, Manufacturing Engineer, Industry, **Design Engineer, Analyst**
5	Mechanical and Thermophysical Properties Developed	Material Engineer, **Design Engineer, Analyst, Statistician**
6	Supplemental Processing and Part Demonstrators	Material Engineer, **Weld Engineer, Machinist, Industry, Design Engineer, NDE Engineer**
7	Component testing in relevant environment with actual operational loads	Material Engineer, Design Engineer, Analyst, **Test Engineer, Quality, Surface Engineer, Tribologist**
8	Production Established – Fully characterized Microstructure (Repeatability and Reproducibility)	Material Engineer, Analyst, **Quality, Statistician**
9	Flight Production and Maturity	Industry

Process Control for New Alloys

AMRL	Attributes	Feedstock Maturity	Parameter Maturity	Machine Configuration	Established Microstructure
1	Basic Concept of Material				
2	Chemical Composition Established through detailed modeling or feasibility through basic parameter development				
3	Feedstock produced and characterized				
4	Parameters and sensitivities established with mature feedstock and Geometric Limitations	Locked			
5	Mechanical and Thermophysical Properties Developed	Locked	Locked		
6	Part Demonstrators and Supplemental Processing	Locked	Locked	Locked	
7	Testing in relevant environment with actual operational loads	Locked	Locked	Locked	Locked
8	Production Established – Fully Characterized Material (Repeatability and Reproducibility)	Locked	Locked	Locked	Locked
9	Flight Production and Maturity	Locked	Locked	Locked	Locked

Material Development (and Selection) All Starts with Requirements and Environments

1) Operate under static and dynamic loads in both tension and compression.
2) Compatible with other materials and fuels and oxidizers (hydrogen, oxygen, hydrocarbons).
3) Integrate multiple subsystems (possibly different metal alloys).
4) Optimized for strength-to-weight ratio (design- and metal-based).
5) Operate in extreme environments (cryogenic and high temperatures, high pressure, combustion, oxidizing or reducing condition).
6) Withstand high thermal gradients and high heat transfer in a high-heat-flux environment.
7) Exhibit high fracture toughness at temperature for potential impacts by domestic object debris (DOD) or foreign object debris (FOD).
8) Exhibit corrosion resistance when in contact with other alloys and operating fluids or contaminants.
9) High wear resistance for contact or running surfaces between components.

Unique alloy requirements for harsh rocket environments

High Conductivity, High Temperature, Oxidation Resistance

High Temperature, Hydrogen Resistant, High Strength-Weight Ratio

Extreme Temperature, Creep and Oxidation Resistant, High Strength-Weight

Extreme Temperature, Burn Resistant in Oxygen

Appropriate Material Definition: Process →Performance

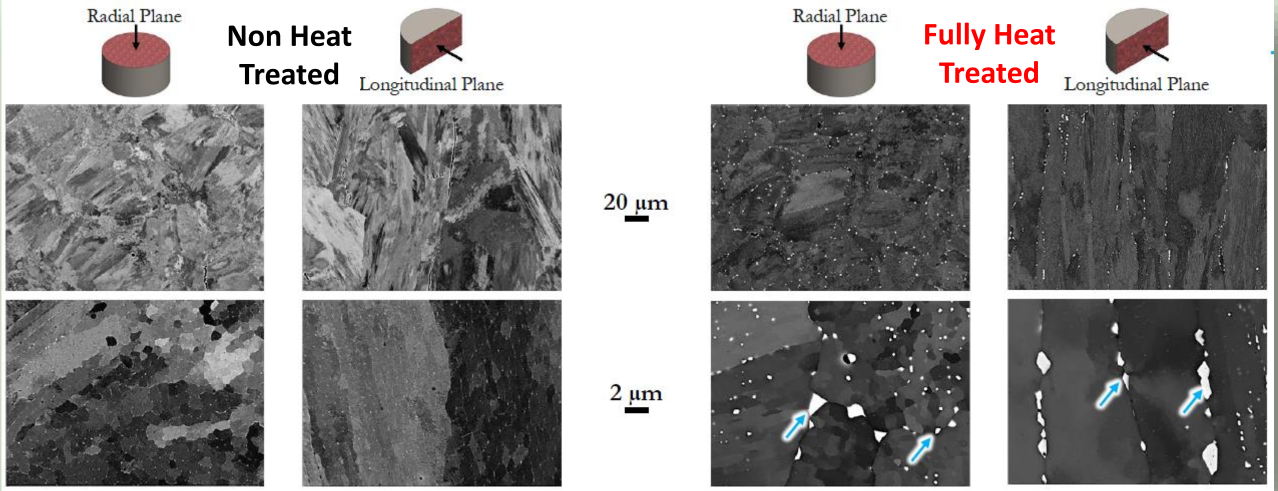
Data from Gradl, Mireles, Protz, Garcia. "Metal Additive Manufacturing for Propulsion Applications", AIAA Progress Series. (2022). Appendix A.

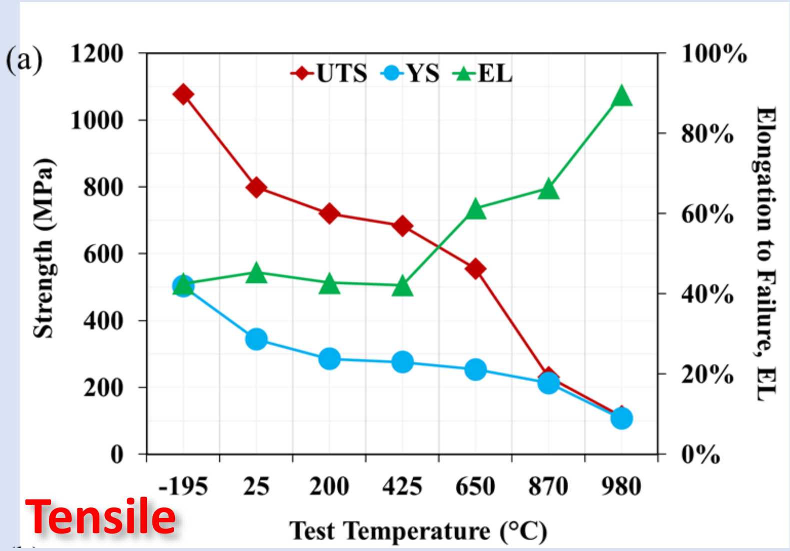
LP-DED Haynes 230

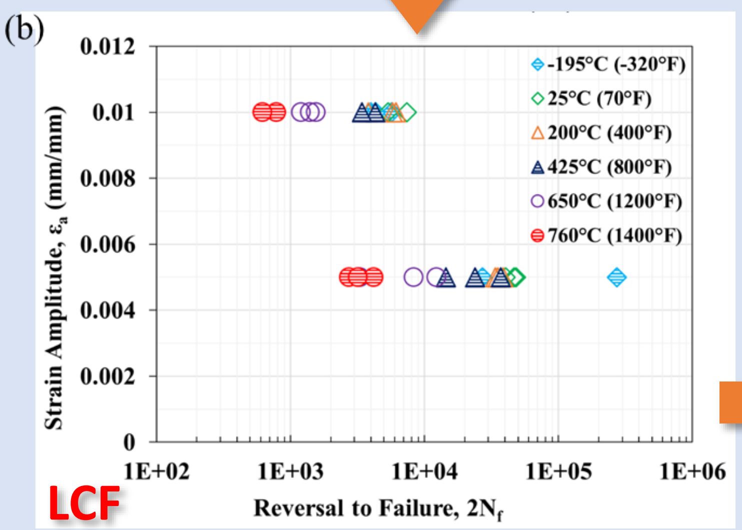
Power (W)	Layer height (µm)	Travel speed (mm/min)	Powder feed rate (g/min)
1070	381	1016	19.10

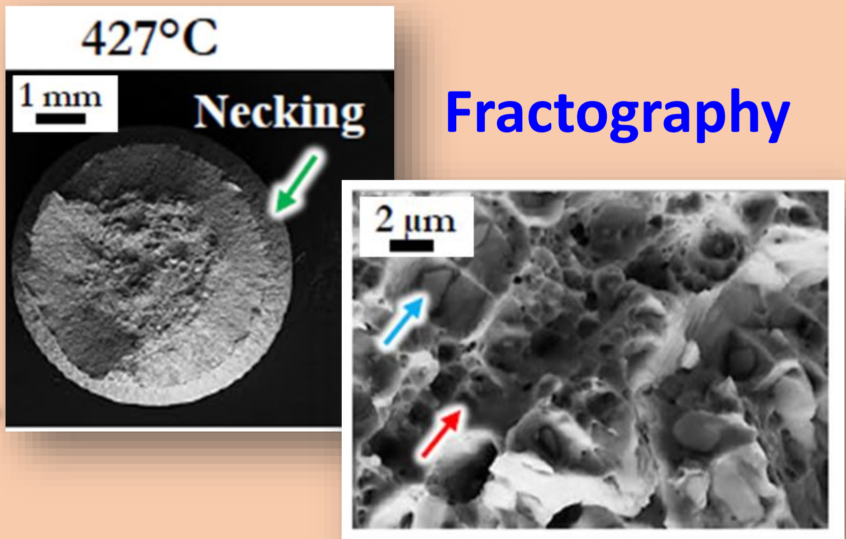
Procedure (Designation)	Temperature (°C)	Time (hrs)	Cooling
Stress Relief (SR)	1066	1.5	Furnace cool
HIP [2]	1163/103 MPa	3	Furnace cool
Solution Annealing (SOL)	1177	3	Argon quench

[2] HIP per ASTM F3301



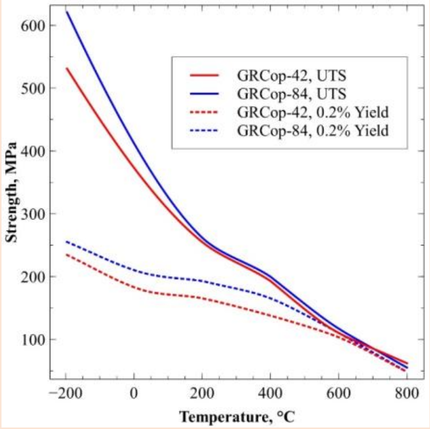


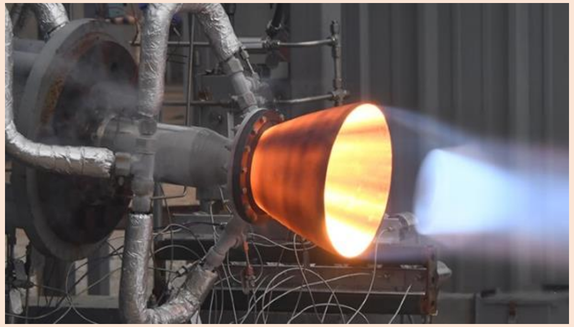




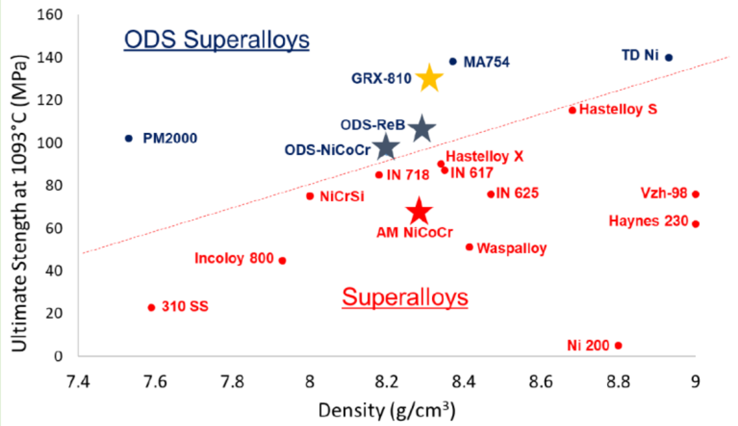
AM Enabling New Alloy Development

GRCop-42, High conductivity and strength for high heat flux applications

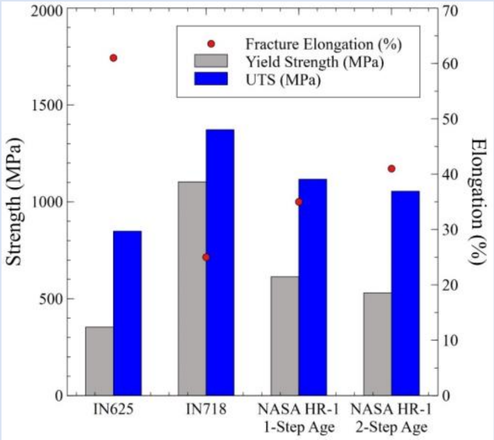


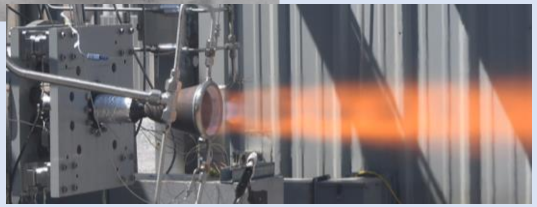


GRX-810, high strength, low creep rupture and oxidation at extreme temperatures

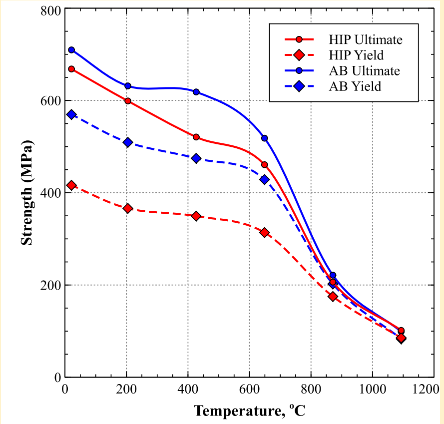


NASA HR-1, high strength superalloy for hydrogen environments





ORCAlloy-21, high strength burn-resistant alloy for oxygen-rich staged combustion



Basic Concept of Material

- Requirements Development for Application.
- Basic Chemical Composition established to meet intended use
  - Includes phase diagram, integrated computational materials engineering (ICME), Calphad.
  - Determine strengthening mechanisms.
  - Consider potential heat treatments.
- Application use case provided.
- Process to produce feedstock and AM Process production hypothesized and documented.

Chemical Composition

- Detailed chemical composition through multiple ICME simulations and mapping of alloy space.
- Methods using Md values, Calphad, or other computation tools and enough simulations to establish a final chemistry and starting process parameters (weldability)
- Initial pilot feedstock may be produced and feasibility parameters established using an AM process
  - Crack susceptibility, melt pool stability
- Chemistry may be adjusted as necessary in later AMRL

1 2 3 4 5 6 7 8 9

Feedstock Produced and Characterized

- Material feedstock produced in pilot batches and scaling plan shown for scale-up production
- Similar equipment shall be used as production batches
- Feedstock has been characterized including chemistry (including any trace elements such as O, C, N)
- If powder, morphology characterization completed including particle size distribution (PSD), morphology, chemistry.
- Initial parameter development on a small development or production machine.
- Initial microstructural characterization coupons and mechanical testing to validate modeling predictions.
- Modifications may be made to the feedstock meet requirements.
- Phase range and melt temperature established with differential scanning calorimetry (DSC).

1 2 3 4 5 6 7 8 9

Parameters and Sensitivities + Geometry

- Scale up feasibility to production AM machine.
- All parameters (infill, upskin, downskin, contour, support) are established and locked. Hardware and software configurations are optimized.
- Heat treatment including stress relief, HIP, and other appropriate processing steps are defined and optimized. Metallurgical samples showing the thermal history have been characterized.
- Initial room temperature mechanical properties established.
- Parameter sensitivity studies completed to determine the optimal operating parameters as well as off nominal behavior.
- Metallurgical samples showing as-built microstructure and parameter sensitivities are documented.
- Design for Additive Manufacturing (DfAM) geometric constraints identified for specific material and AM method (smallest features, repeatability, distortion, thin-walls, overhang angles, surface texture, etc)
- Complete mapping of the build volume to determine variations including any knit lines between overlapping energy sources.
- Determining and understanding defects that might be alloy specific.

1 2 3 4 5 6 7 8 9

Material Properties – Mechanical and Thermophysical

- Key **application** mechanical and thermophysical properties per ASTM standards are established across the operating ranges (+/- margin) and well documented.
  - Tensile properties vs temperature.
  - Fatigue SN curves for low cycle and high cycle regimes have been established including application use temperatures at various strain amplitudes and stress ranges.
  - Thermophysical properties such as thermal conductivity and coefficient of thermal expansion.
  - Fracture toughness.
  - Crack growth.
  - Creep Rupture.
- Fractography has been completed on all fatigue and tensile surfaces and reported to understand failure mechanisms.
- Initial feasibility of properties in specialty environments (corrosion, hydrogen, creep)
- Thin-wall mechanical testing (tensile and fatigue) that correlates to wall thicknesses used for actual parts.
- S-basis followed by B or A-basis for full maturity as required.

1 2 3 4 **5** 6 7 8 9

Supplemental Processing and Part Demonstrations

- Build interruptions evaluated and documented.
- Evaluation of material using non-destructive evaluation (NDE) techniques
- Machinability parameter studies completed to determine tooling for final interface machining (lathe, milling, EDM, etc.)
- Joining studies (welding, brazing, diffusion bonding) completed for joining parts to determine feedstock for joining, metallography completed and documented.
- Complete trial builds of demonstration parts using material and process.
- Volumetric sectioning of parts to determine microstructure and variations between thick and thin regions.

1	2	3	4	5	6	7	8	9

Testing in relevant environment with actual operational loads

- Test parts built and successfully processed.
- Component testing in a relevant environment that simulates end use environmental loads (hot-fire testing and rapid thermal heating and gradients).
- Parts sectioned post-testing to determine how material responded and condition post-testing.
- Duty cycle testing completed to help correlate mechanical property data to actual parts.
- Propellants, fluids, or other material compatibility at interfaces with the AM material should be evaluated.
- Application specific testing such as corrosion, hydrogen, etc should be completed to determine compatibility and life using the AM material.
- Specialty testing may also include weld design allowables.
- Fully characterized metallurgical process documented.

1 2 3 4 5 6 7 8 9

Production Established and Fully Characterized Microstructure

- Feedstock recycling studies completed and documented using multiple feedstock suppliers (if required) and heats.
- Design allowables established and sufficient testing completed to understand variation and minimums.
- All prior steps completed and fully documented and production planning locked down.
- Process control charts and long-term monitoring strategy established.
- Fracture control planning and testing.

Flight Production and Maturity

- Industry material specifications are mature.
- Material has flown successfully.
- Optional sectioning of hardware post-flight.
- Statistical derived datasets broadly applicable across industry.

1 2 3 4 5 6 7 8 9

Adoption and Infusion

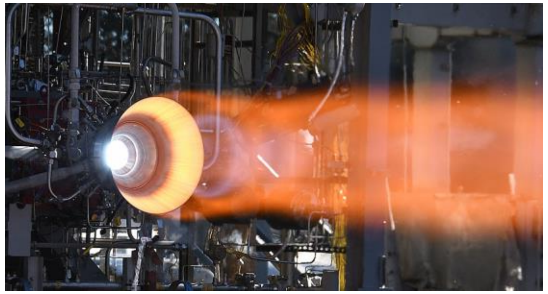
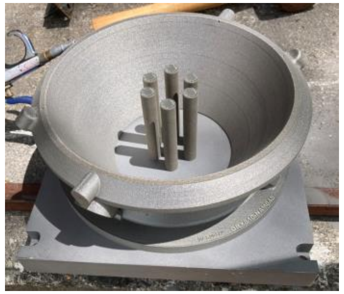
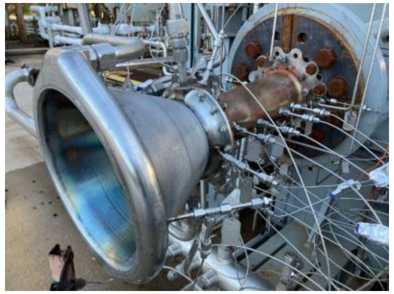
- Adoption means that you no longer have full control of the research and application and use of the alloys.
- This means you must develop a robust enough material, supply chain, and ecosystem to support commercial adoption.
- Follow this “recipe” and you should get this material.
- Provide enough publicly available documentation – parameters, properties, lessons learned, supplemental processing.
- There are no surprises and test data should be “boring”.

Do you check all these boxes?

What additive material readiness level are you?

Summary and Future Work

- We generally expect that a metal alloy is mature before we continue with qualification of this alloy – but what does that mean? How do we have confidence?
- **A common approach is necessary to allow for maturity and infusion of new alloys.**
- Proposing an additive material readiness level (AMRL) with developmental steps and rigor for full application infusion.
- Common alloys likely hit AMRL 8/9 level due to all the work across industry but need to be evaluated for each application, process, machines, etc.
- Not time gated or serial, but tailored tasks based on the end use application.

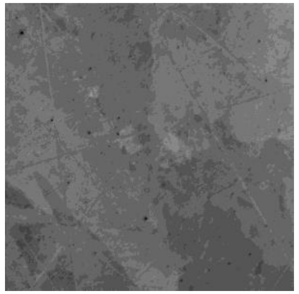
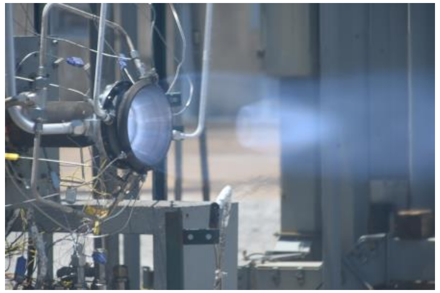



Image from Artemis II Mission, April 2, 2026

Image from Artemis II Mission, April 6, 2026

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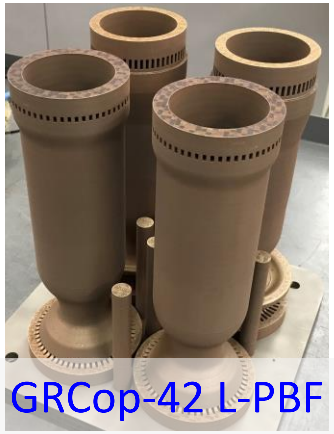
What is required to properly mature aerospace alloys?

1. Application Requirements and Basic Concept of Material.
2. Chemical Composition Established through detailed Modeling.
3. Feedstock Produced and Characterized.
4. Parameters and sensitivities established with mature feedstock, geometric limitations.
5. Mechanical and thermophysical properties developed and characterized.
6. Supplemental processing and Part demonstrators.
7. Testing in a relevant environment with actual operational loads.
8. Production established and fully characterized metallurgy.
9. Flight production and maturity.

NASA Alloy Development to Improve Performance

Max. Use Temp. (°C)	Alloy Family	Purpose	Novel AM Alloys	Propulsion Use
200	Aluminum	Light weighting	-	Various
750	Copper	High conductivity; strength at temperature	GRCop-42 GRCop-84	Combustion Chambers
700	Iron-Nickel	High strength and hydrogen resistance	NASA HR-1 NASA HR-2 JBK-75	Nozzles, Powerheads
800-1100	Nickel	High strength to weight Burn-Resistance	ORCAlloy-21 Alloy 754-ODS OR-F1	Preburners, Injectors, Turbines
1100	ODS Nickel	High strength at elevated temp; reduced creep	GRX-810 Alloy 718-ODS	Injectors, Turbines
1850	Refractory	Extreme temperature	C-103, C-103-CDS, Mo, W	Uncooled Chambers


GRCop-42 L-PBF


NASA HR-1 LP-DED

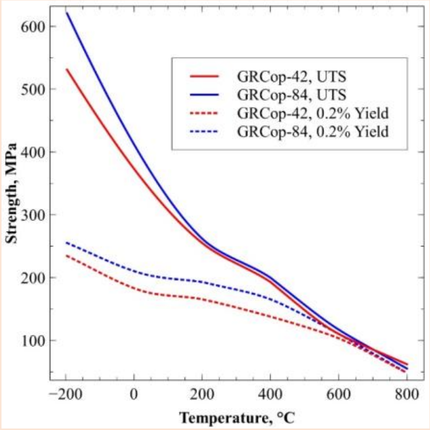

GRX-810 L-PBF

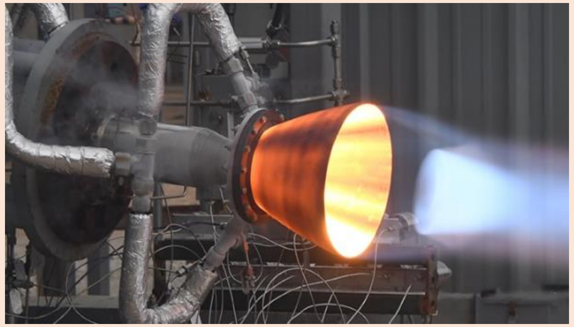

C103 L-PBF

New alloy development using various additive manufacturing processes (PBF and DED) can yield performance improvements over traditional alloys

AM Enabling New Alloy Development

GRCop-42, High conductivity and strength for high heat flux applications





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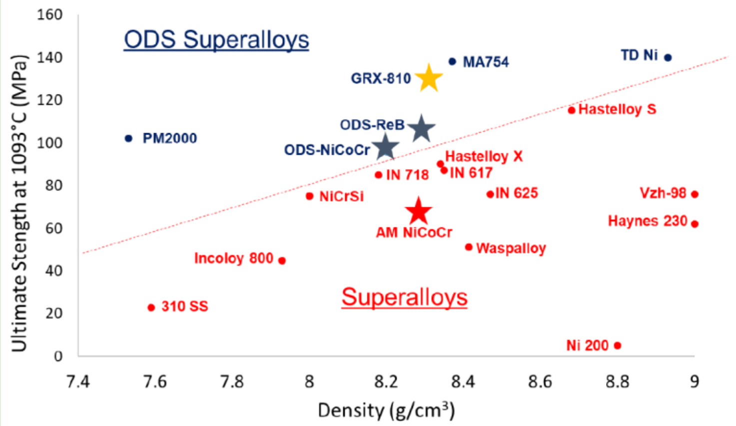

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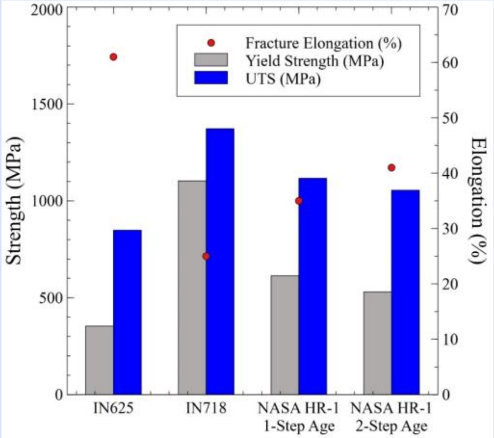
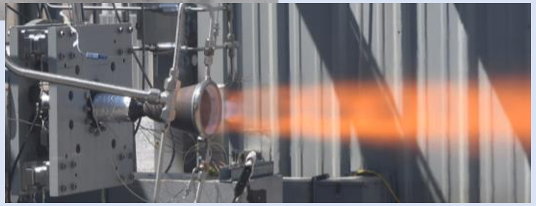
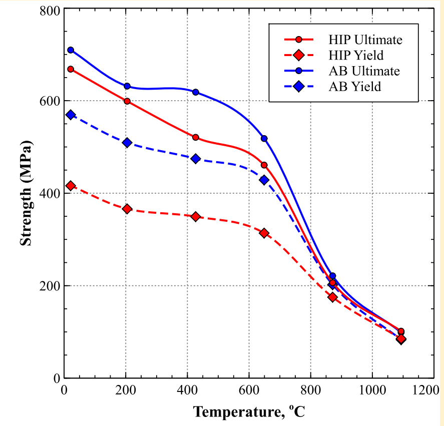




ORCAlloy-21, high strength burn-resistant alloy for oxygen-rich staged combustion



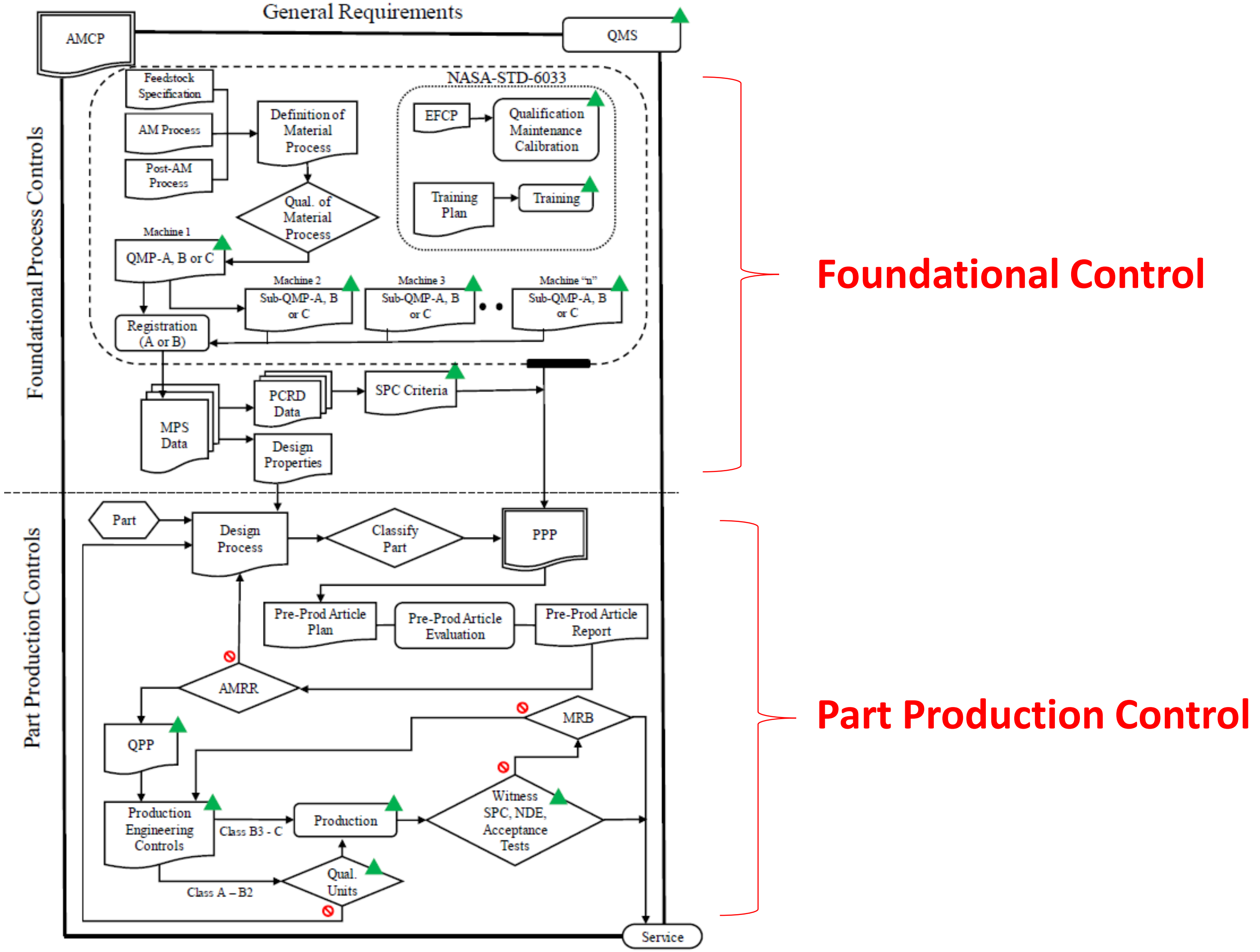
Proper Processing Requires Guidelines

What should I worry about?

How should I define and control them?

Who and When should work them?

How Customer/NASA should be aware and approve of them?



115 "shall" requirement statements in 6030; 31 "shall" statements in 6033

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