PARSEC

Plume Additive for Reducing Surface Ejecta and Cratering

2024 Human Lander Challenge

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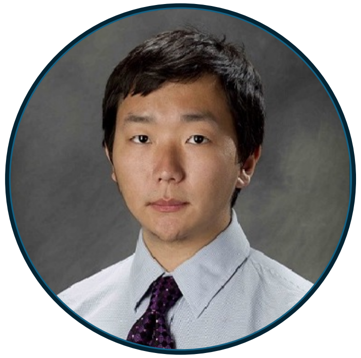

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Agenda

Introduction → Solution → Verification & Validation → Budget & Timeline → Conclusion & Next Steps

Introduction
Plume Surface Interaction (PSI)

- Danger to landers (Watkins et al., 2021)
  - Destabilizes landing site
  - Disrupts sensors and visuals
- Danger to surrounding assets
  - Ejected particles can sand blast assets

Rightward of 11817, showing the dramatic tilt of the spacecraft. (NASA, 2016)

Introduction

Plume Additive for Reducing Surface Ejecta and Cratering (PARSEC)

- Returning to the Moon
  - Artemis will face challenges with PSI
- PARSEC
  - Physically mitigate PSI
  - Create safer landing conditions
  - Protect lunar assets

Artemis Logo. (NASA, 2023)

Agenda

Introduction

Solution

- **Design Overview**
- **Deployment**
- **Additives**

Verification & Validation

Budget & Timeline

Conclusion & Next Steps

Solution

PARSEC – Trade Study for Mitigation Methods

- Compared seven solutions against technical criteria
- Ultimately determined a plume additive approach

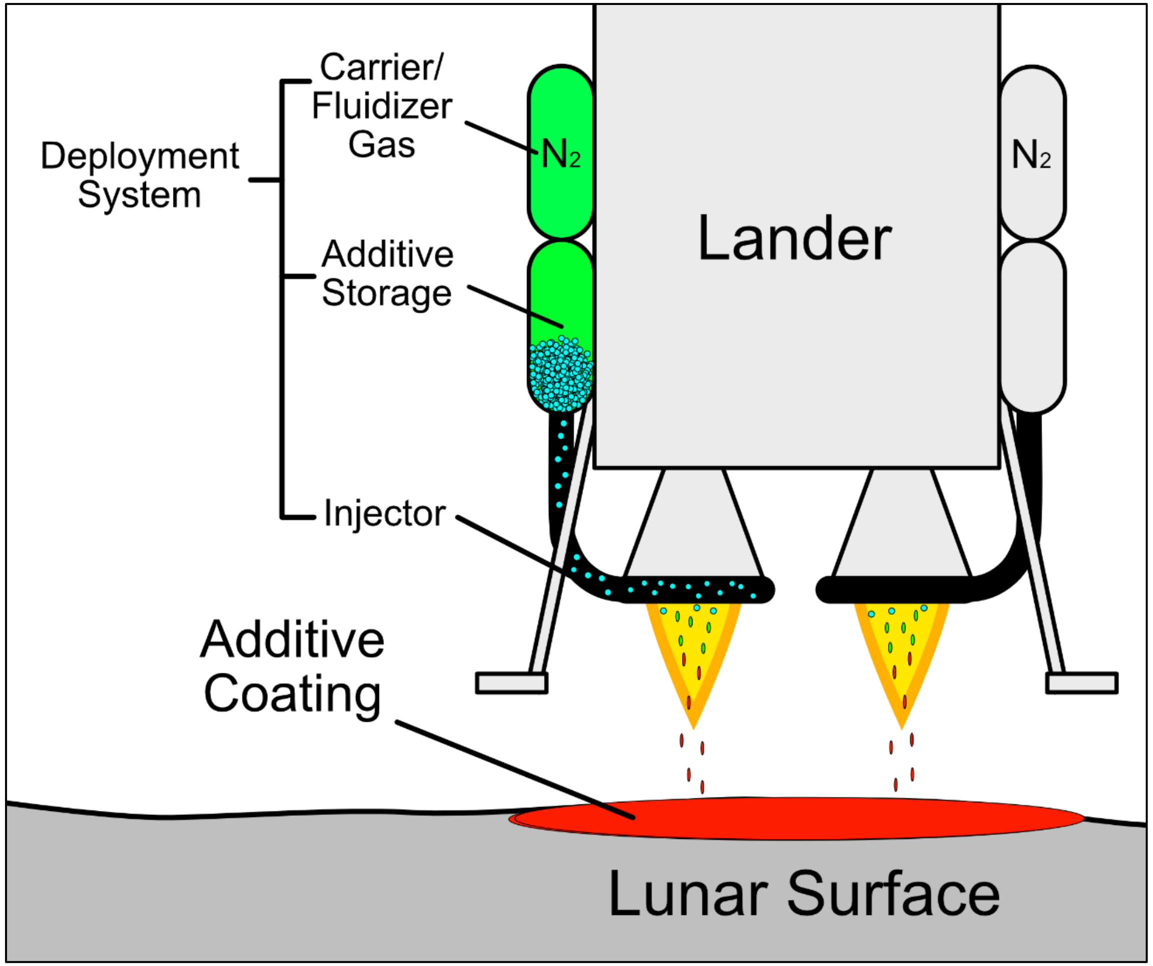
Mitigation Methods			Scores	Trades						
Criteria	Mandatory? (Y=1/ N=0)	Weight	Scale	Deployable Landing Pad (Cargo Drop)	Landing Boosters at top	Ballistic Landing	Electrically Charged Soil	Change Shape and Angle of plume	Exhaust Additive to create Landing Pad	Melt Regolith from Lander
Modifications Required	0.5	8%	1-3	2.5	1	2	2.5	1.5	2.5	2.5
Current Understanding	0	10%	1-3	3	2	3	1	1.5	2	1.5
Available Information	1	5%	1-3	2.5	3	2.5	2	1.5	2.5	2
Reusability	0	5%	1-3	3	3	2	3	2.5	3	3
TRL	0	5%	1-3	1	2.5	3	1	1	1	1
Mass	0	15%	1-3	1	2	3	3	3	3	3
Volume	0	8%	1-3	1	3	3	3	3	3	3
Cost	0	8%	1-3	1	2	2	2.5	2	2.5	1
Power	0	5%	1-3	3	3	3	2	3	3	1
Effectiveness	0	8%	1-3	3	2	3	1.75	1	2	2.5
Complexity	0	8%	1-3	1	2	3	1.5	2	2	1
Safety	1	15%	1-3	3	2	1	3	2.5	3	1
Weighted Total %		100%		69%	73%	82%	77%	71%	85%	63%

Solution

PARSEC – System Overview

Plume Additive for Reducing Surface Ejecta and Cratering

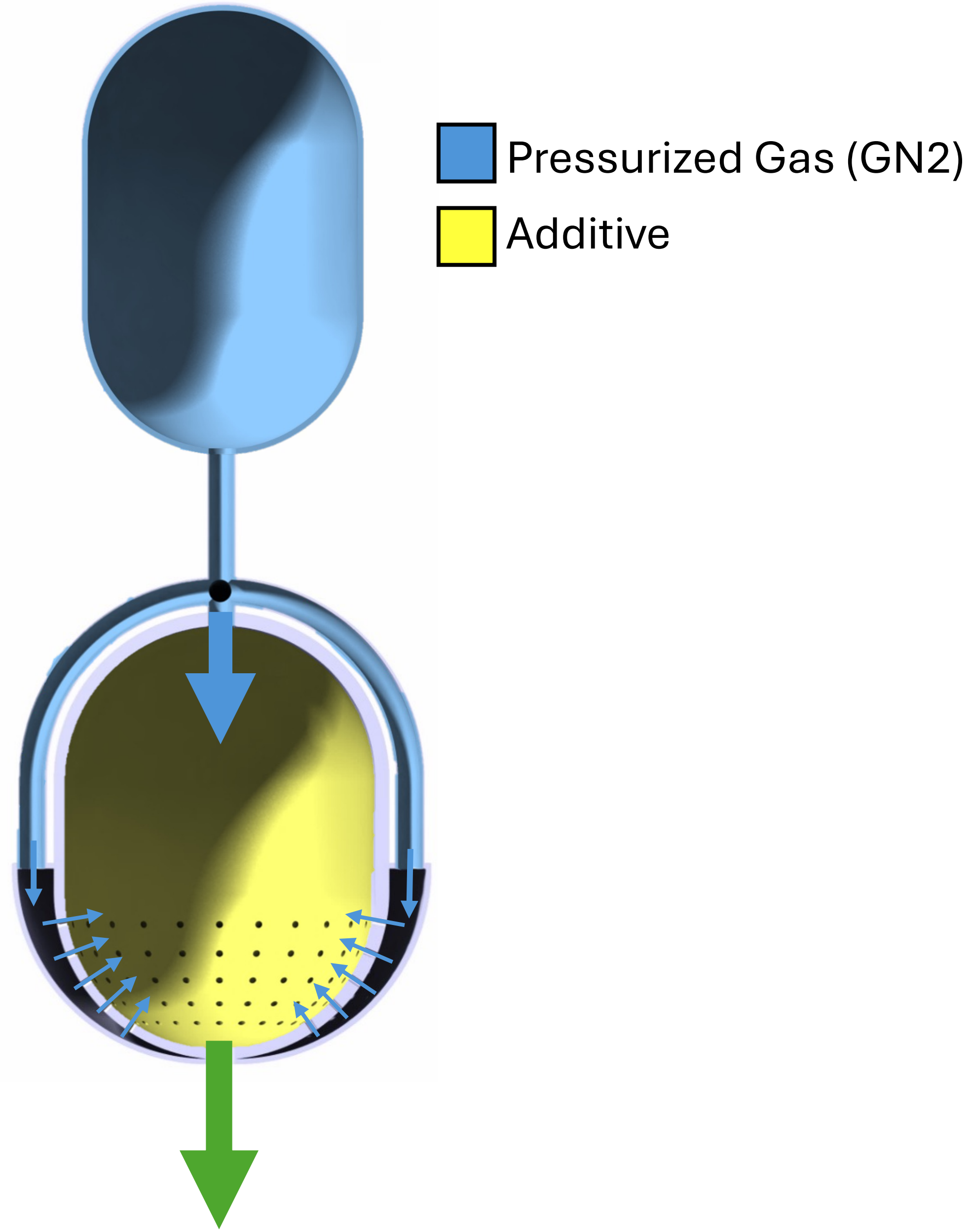
- Additive injected into plume, like thermal spraying
- Melted additive conglomerates regolith particles
- Particles come together to form solid landing pad



Solution

Deployment – System Concept

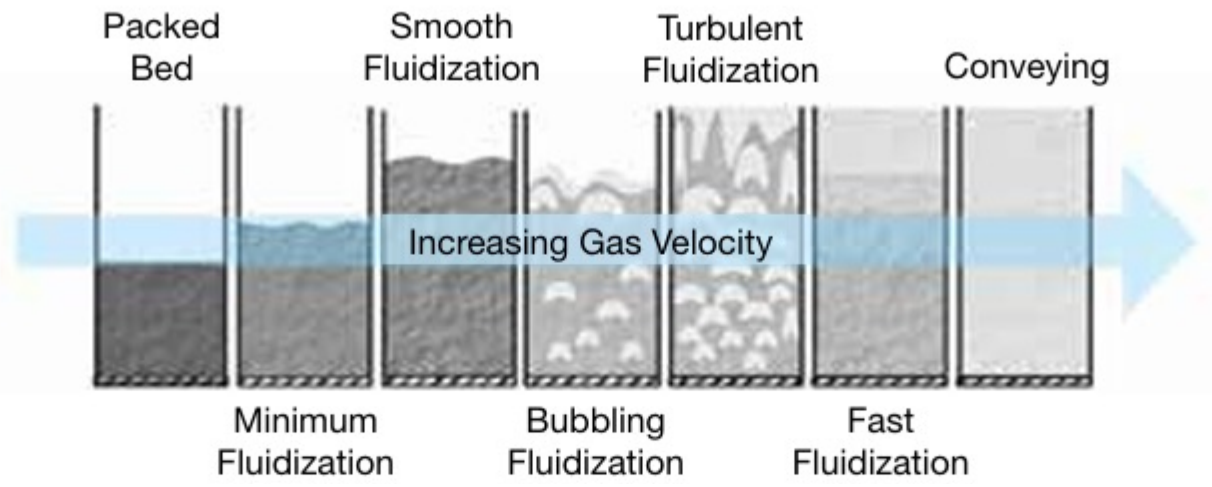
- Combines both Fluidization and Thermal Spraying
- Made for minimal modification of lander



Solution

Deployment – Fluidization

- Move solids like fluids (Shabanian et al., 2012)
- Increase in heat transfer (Cocco et al., 2014)
- Evenly distribute additive

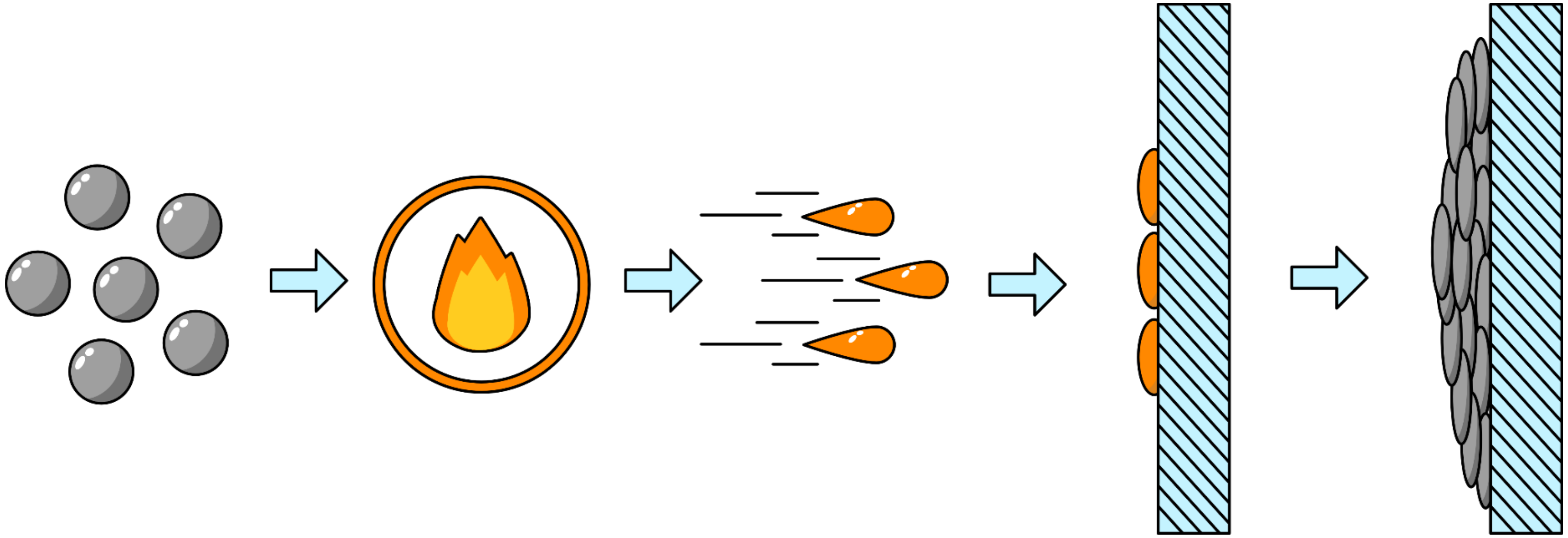


Different types of fluidization (Cocco et al., 2014)

Solution

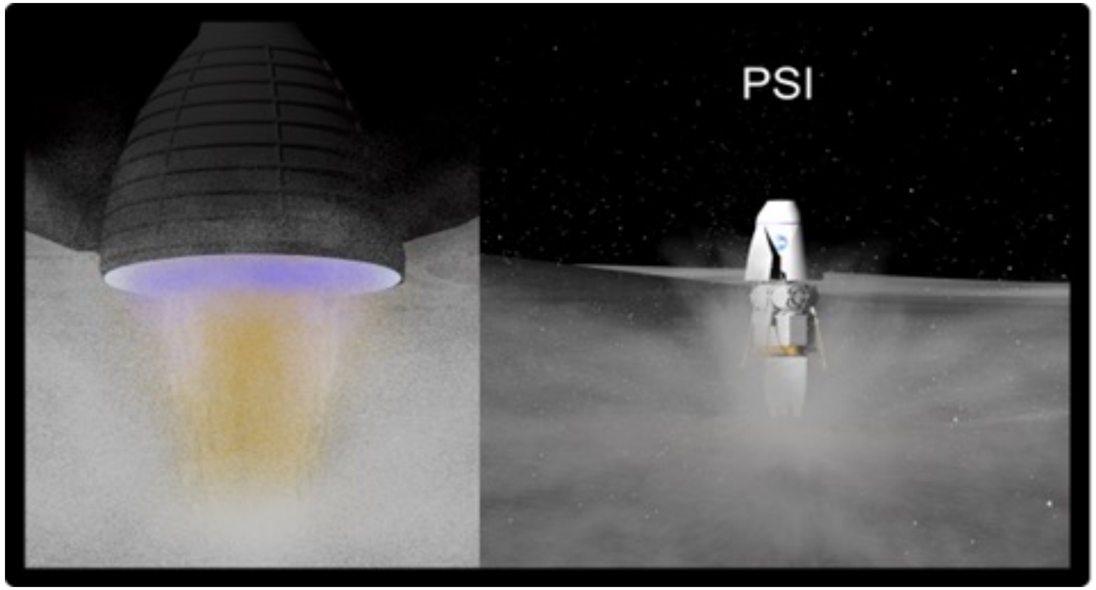
Deployment – Thermal Spraying

- Fine ceramic or metal particles are melted and accelerated (Cañas et al., 2023)
- Melted particles form a protective coating on part surfaces
- Scaled-up process could be done over the lunar surface (Astrobotic, 2021)

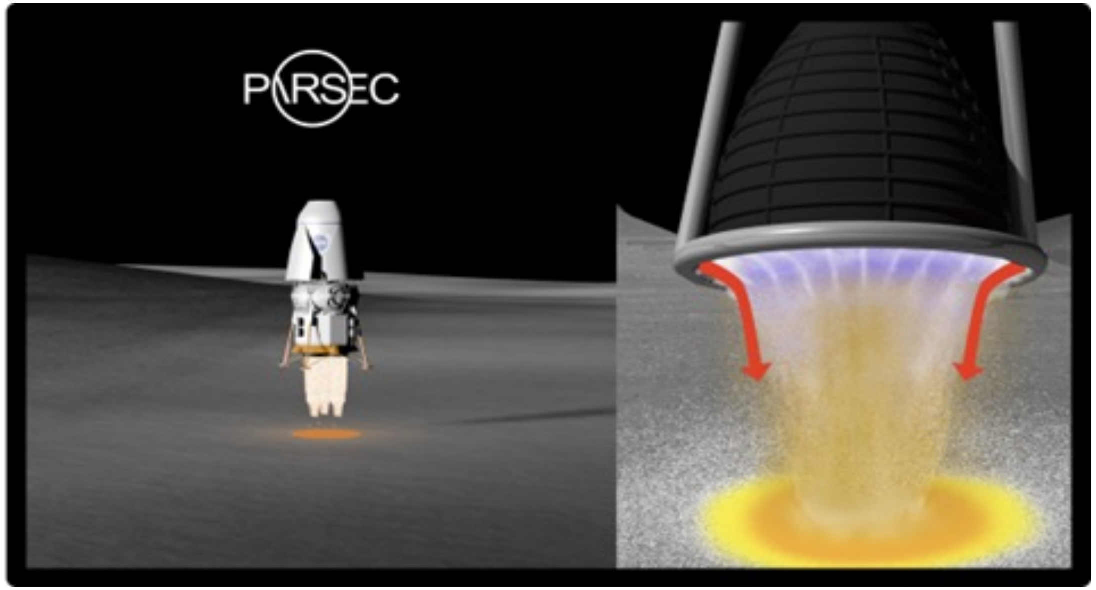


Solution

Deployment – Integrated System



Before

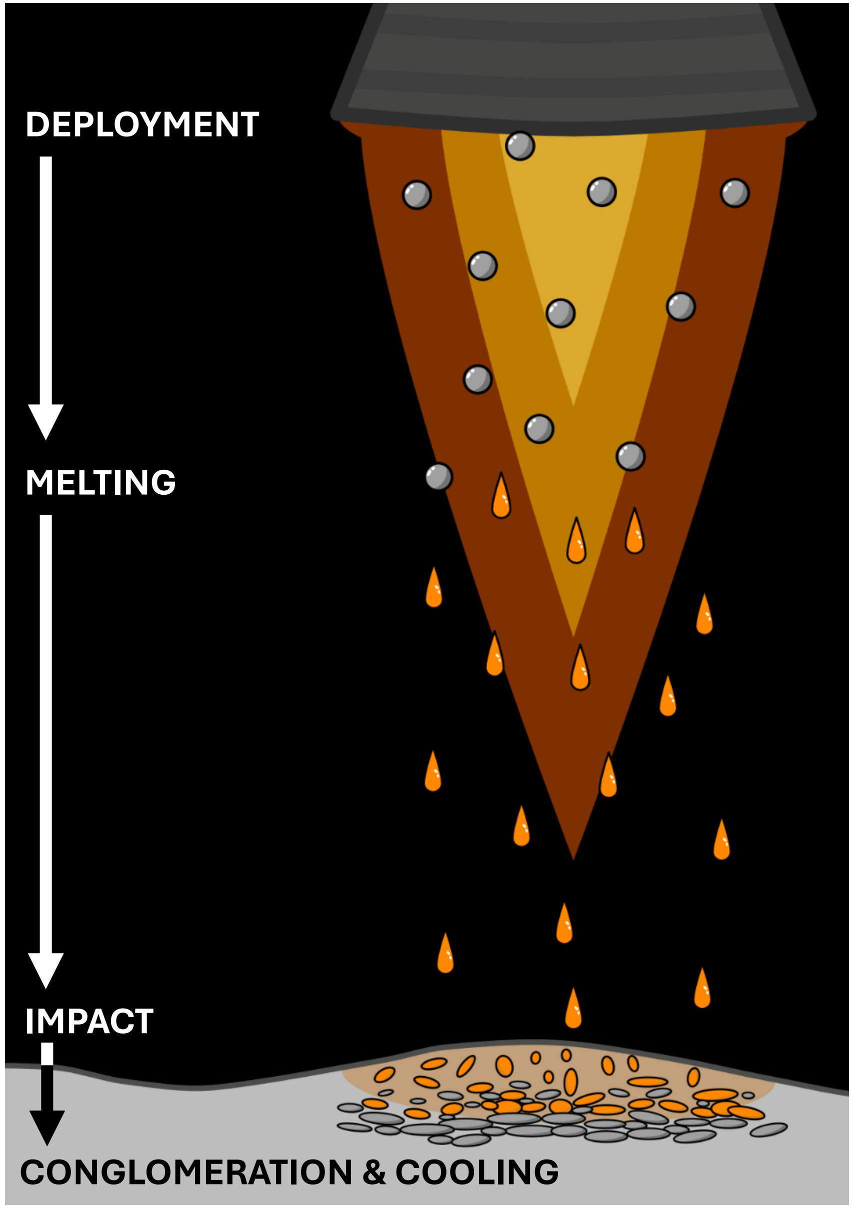


After

Solution

Additives – Definition

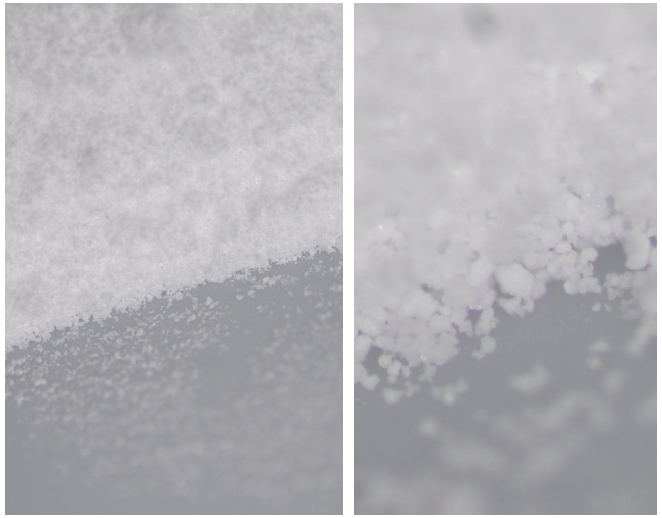
- Technical ceramics and metals that will be injected into plume
- Desired properties:
  - Strength to survive plume
  - Melting point < 3000 K
  - High thermal shock resistance
  - High fracture toughness
  - Low cost & mass



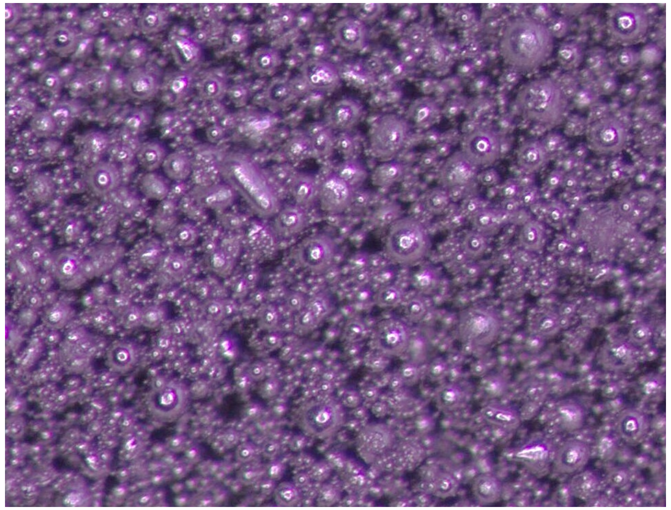
Solution

Additives – Candidates

- Main additives
  - Alumina
  - Zirconia-toughened alumina (ZTA)
  - Yttria-stabilized Zirconia
  - Nickel alloys
- Other additives
  - Si_3N_4 & AlN sintering to form SiAlON
  - Thermite reactants



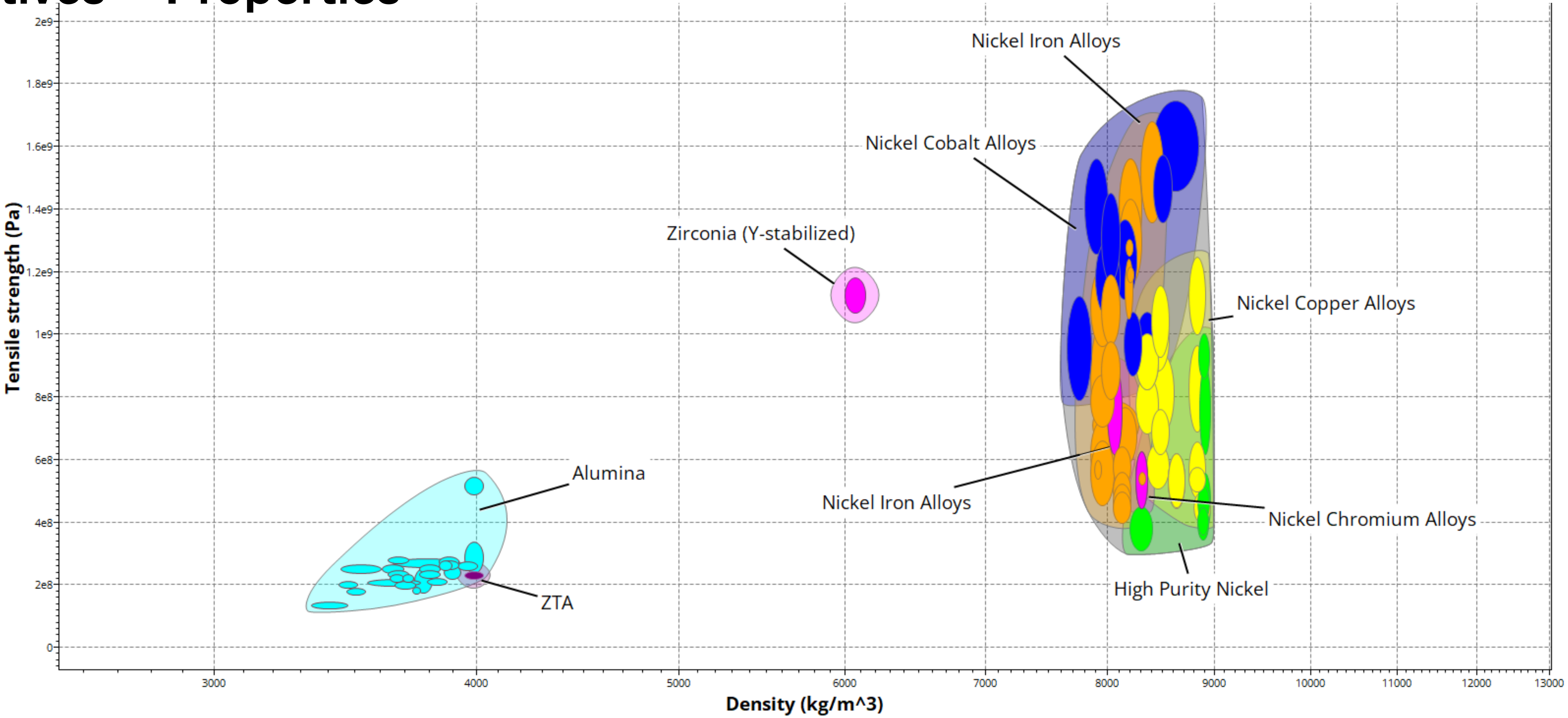
Alumina Powder in Optical Microscope



Nickel Alloy Powder in Optical Microscope

Solution

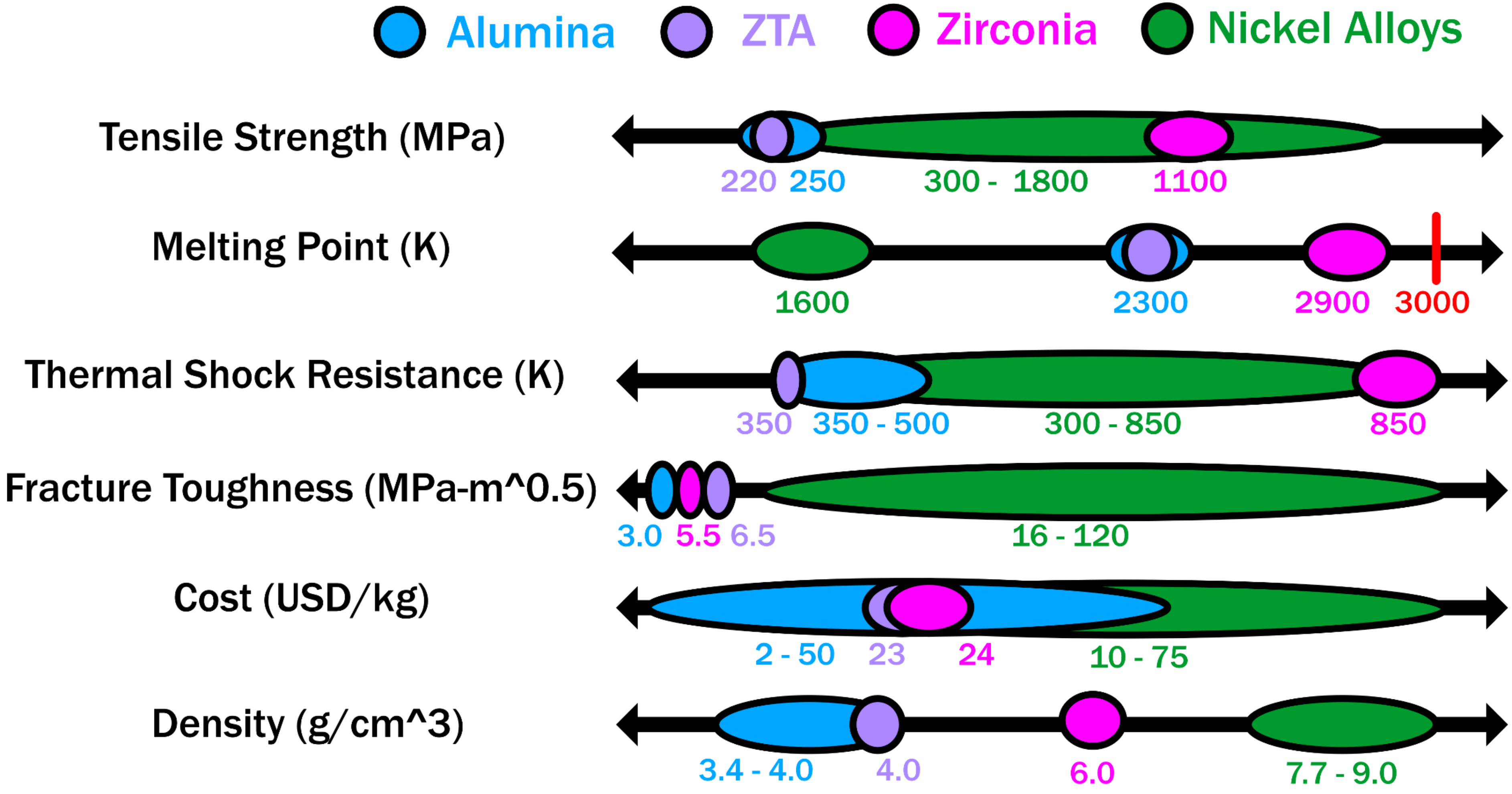
Additives – Properties



Additives Tensile Strength v. Density Plot (ANSYS® Inc., n.d.)

Solution

Additives – Properties (cont.)



Solution

Additives – Summary

Alumina

- Cheapest
- Least dense
- Moderate melting point (2300 K)
- Lowest tensile strength

Y-stabilized Zirconia

- Highest thermal shock resistance
- Tensile, flexural strength > alumina
- Moderate density
- Highest melting point (2900 K)
- Lowest thermal conductivity

ZTA

- Highest fracture toughness
- Moderate melting point (2300 K)
- Similar density to alumina
- Flexural strength > alumina
- Lowest thermal shock resistance

Nickel

- Highest thermal conductivity
- Lowest melting point (1600 K)
- Highest ductility
- Variable mechanical properties
- Most expensive & dense
- Suspected cancer hazard (Gates, 2023)

Agenda

Introduction

Solution

Verification & Validation

- Experiment
- Numerical Simulation
- V & V
- Risks

Budget & Timeline

Conclusion & Next Steps

Verification and Validation

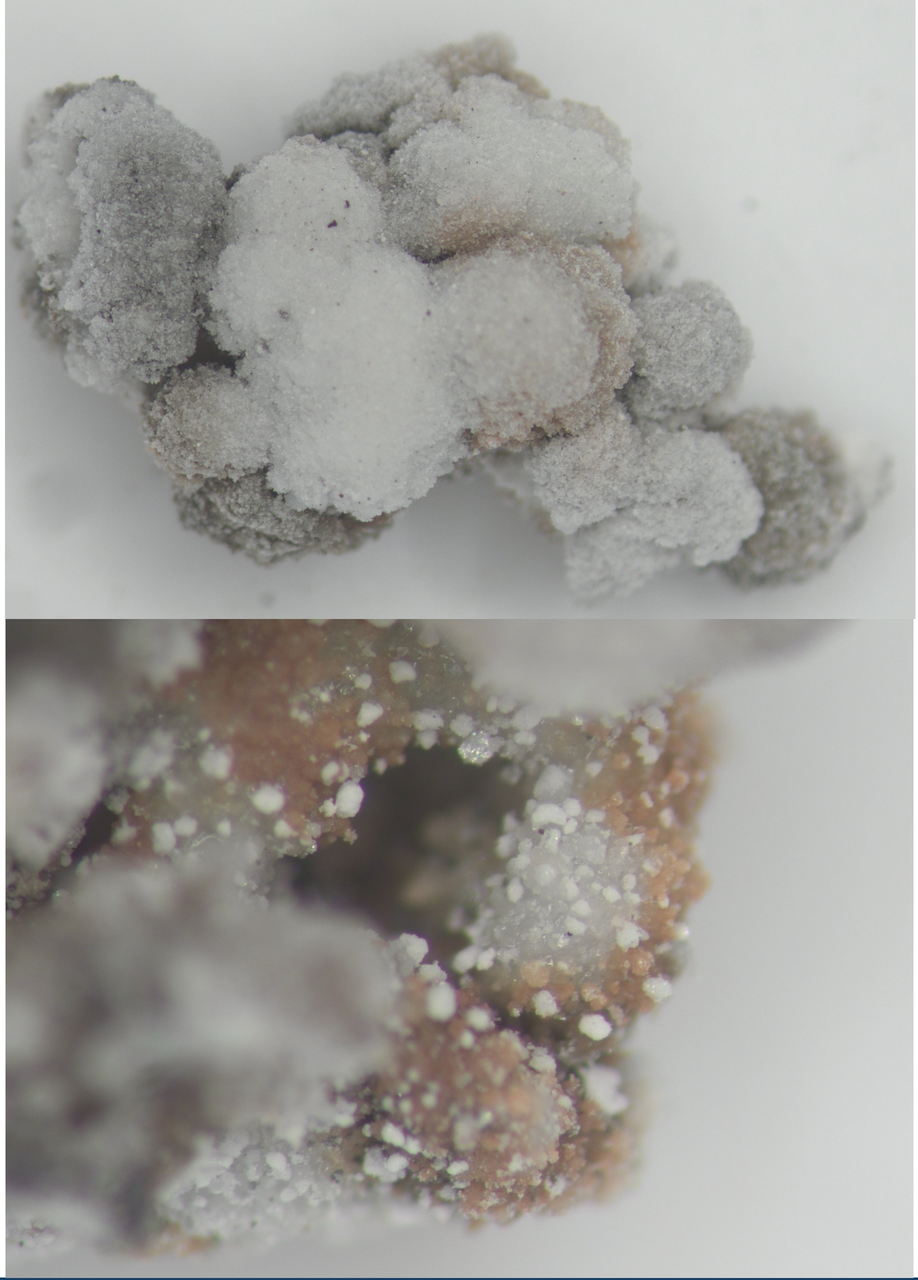
Experiment – Conditions

- Test for conglomeration
- 18 tests in total using
  - Alumina particles
  - Buildup #22 (nickel alloy)
- Scaled down rocket engine tests with
  - Sand
  - Fire Brick
  - LSP-2 Lunar Regolith Simulant

Verification and Validation

Experiment – Alumina Result

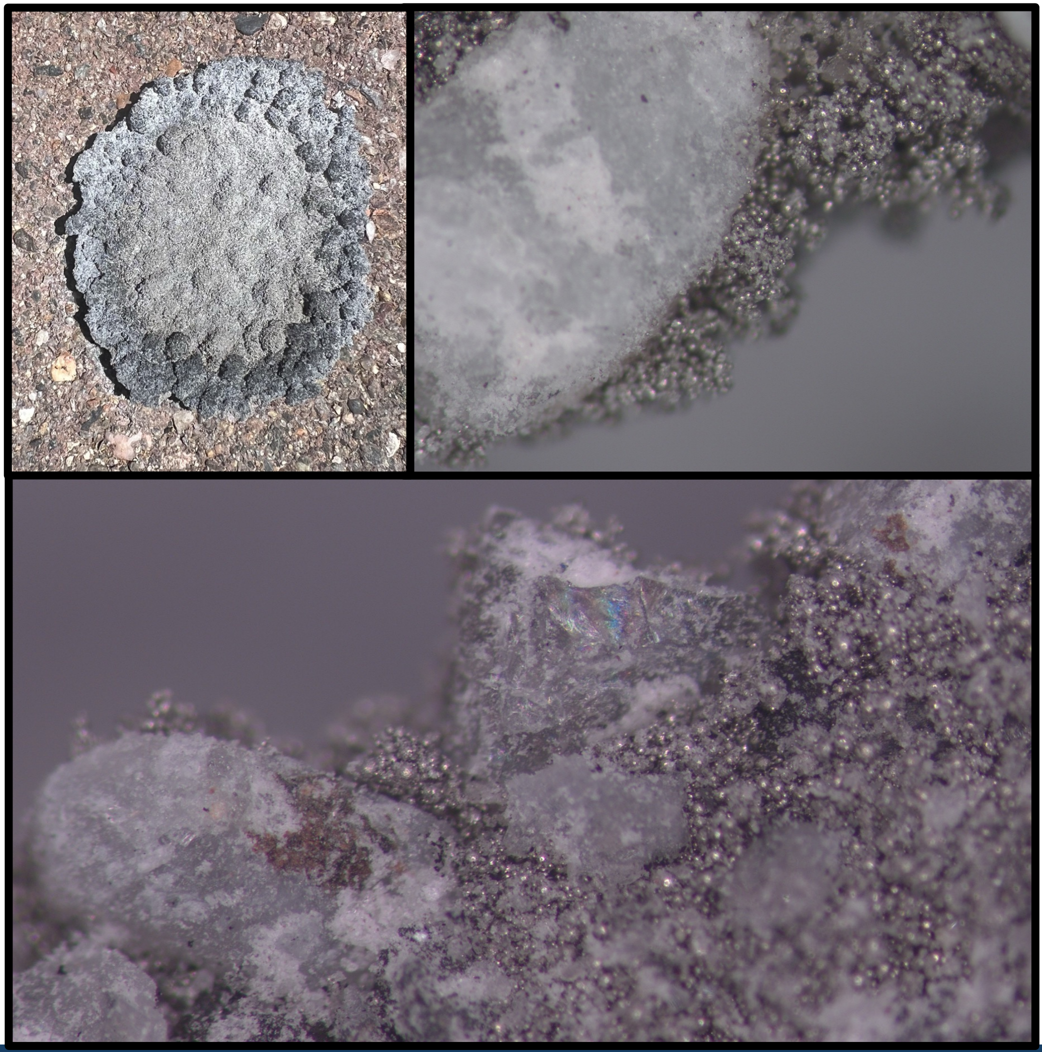
- Minor conglomeration
- Frail pad formations that fractured
- Issues outside of PARSEC's control:
  - Additive clog
  - Temperature/thermal properties not high
- Inconclusive

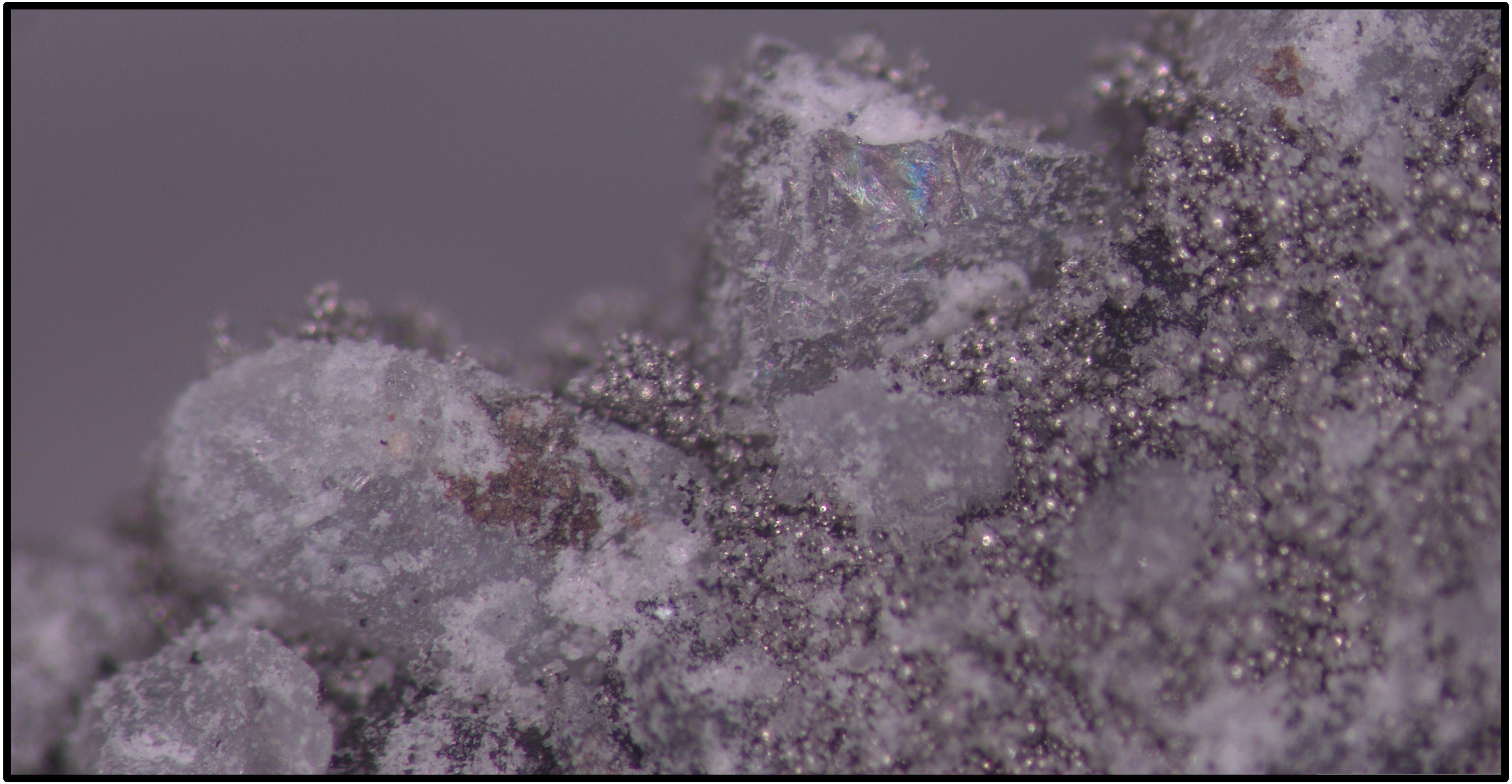


Verification and Validation

Experiment – Nickel Result

- 100% success rate
- Pads 3-6cm diameter
- Pads 0.5-1cm in depth
- Long lasting and strong

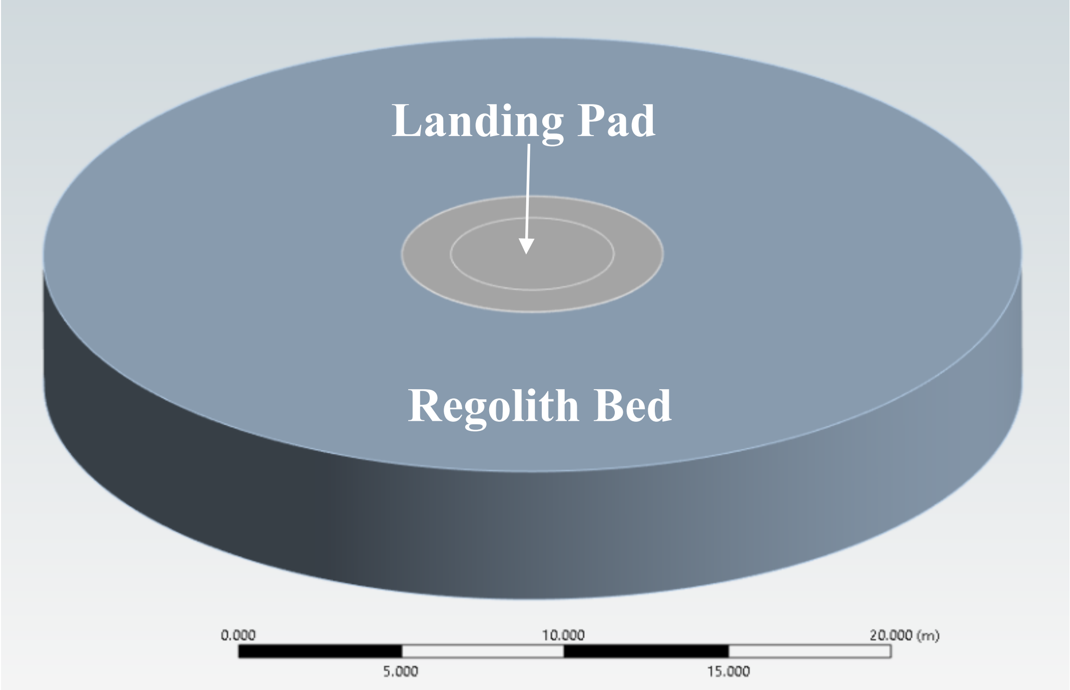




Verification and Validation

Simulation – Model

- Analysis in ANSYS Mechanical
- Regolith bed:
  - 30m diameter; 5m depth
  - Isotropic elastic modulus equal to deformation modulus of regolith
- Pad assumptions:
  - Particle-reinforced composite
  - Isotropic elasticity
  - No pores or voids
  - Obeys rule of mixtures (Li et. al. 2001)

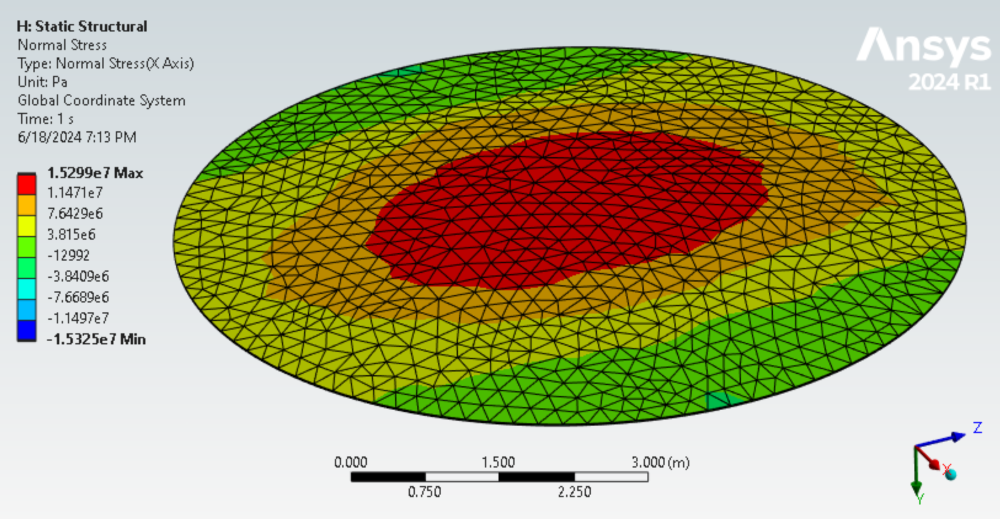


Landing pad and regolith bed models (ANSYS® Inc., n.d.)

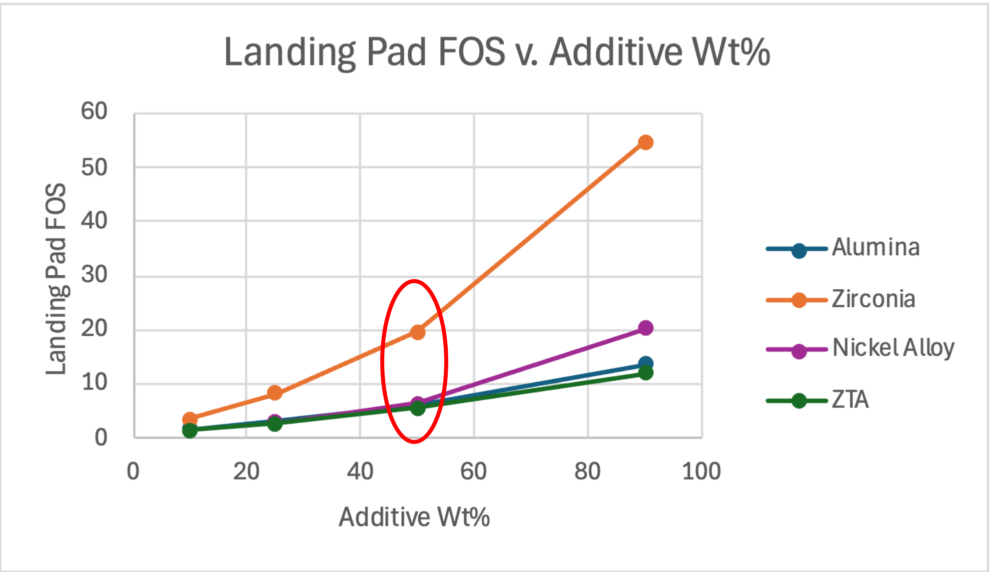
Verification and Validation

Simulation – Result

- Simulated various landing pad sizes
- Calculated factors of safety with:
  - Estimated pad tensile strength
  - Max tensile stress from simulation
  - Additive weight percentage
- Optimal Pad Properties:
  - 8m Diameter
  - 2cm Thickness
  - 50 wt% additive



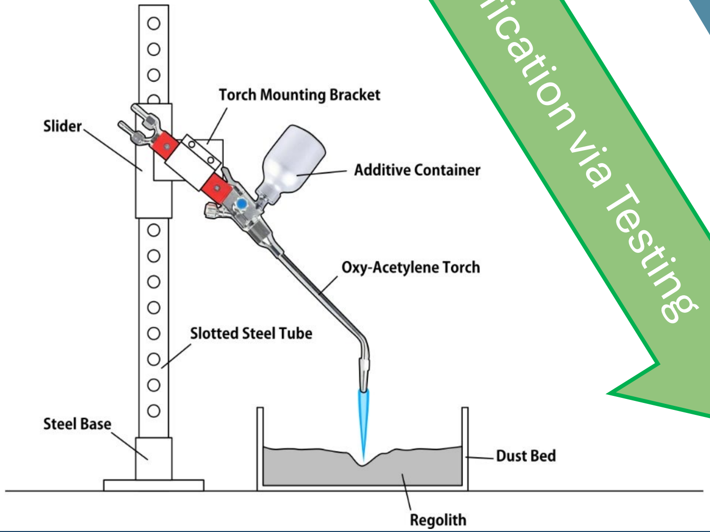
X-axis normal stress plot for 8m x 2cm pad (ANSYS® Inc., n.d.)

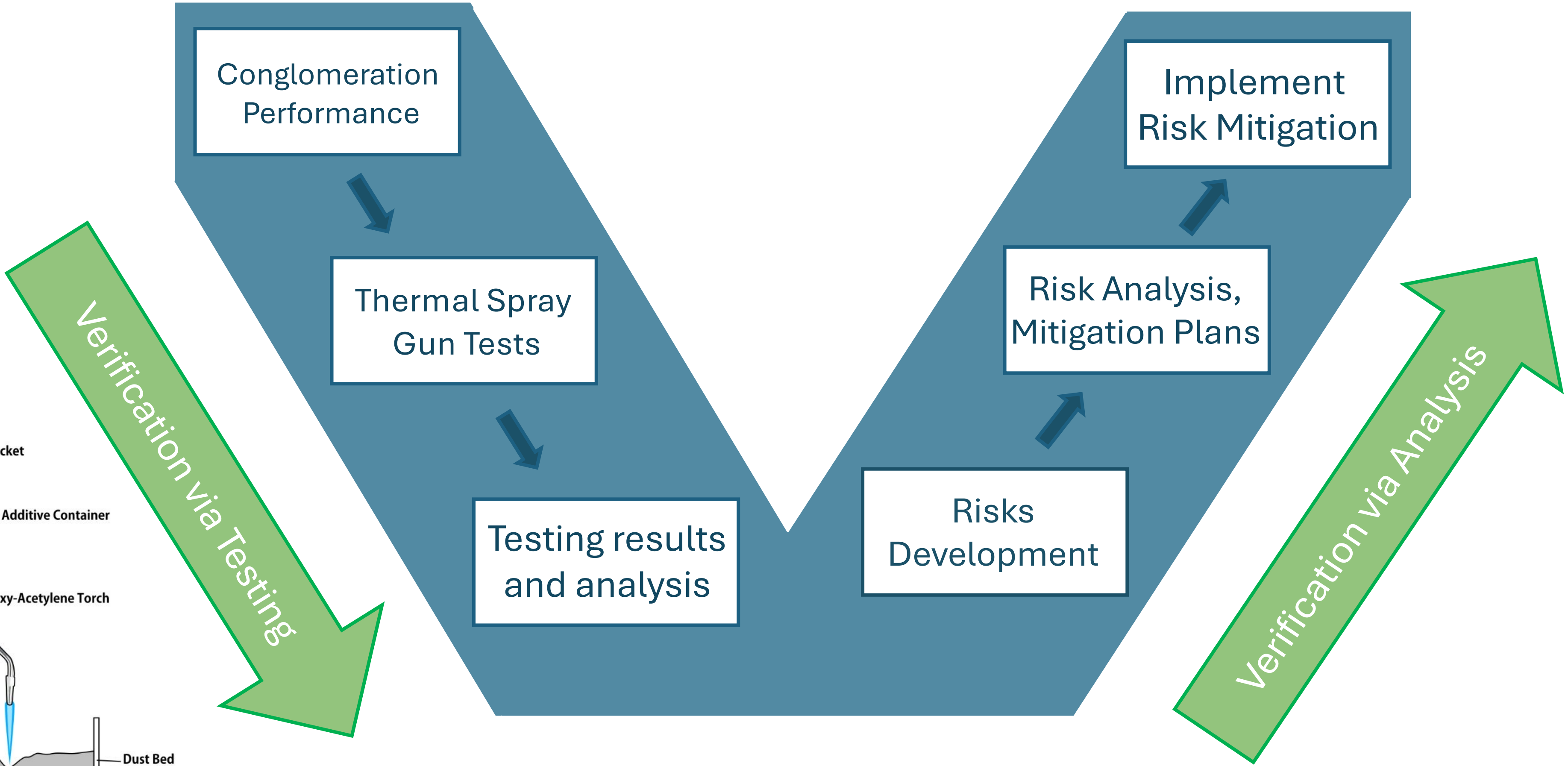


FOS vs. Additive Wt% for 8m x 2cm pad

Verification and Validation

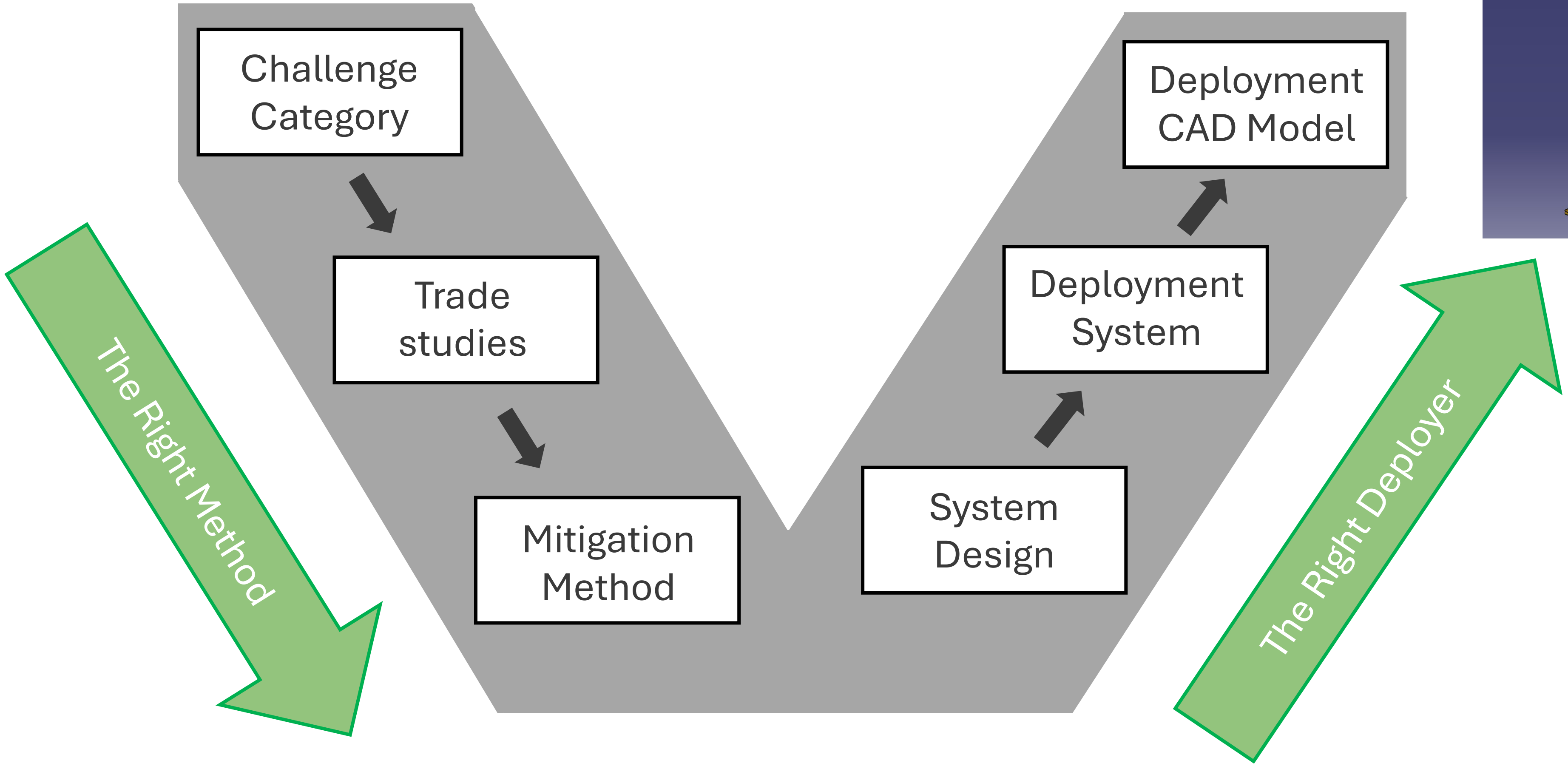
Verification Process

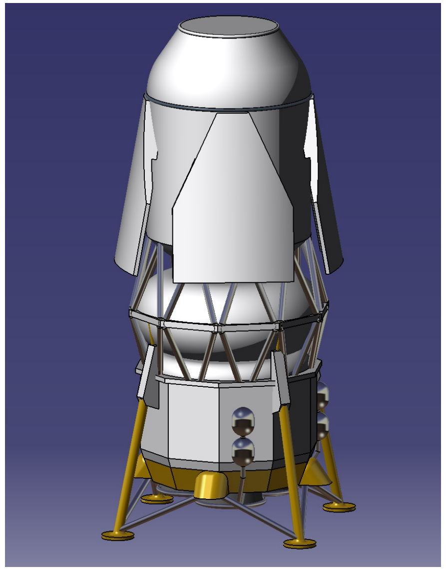




Verification and Validation

Validation Process





Verification and Validation

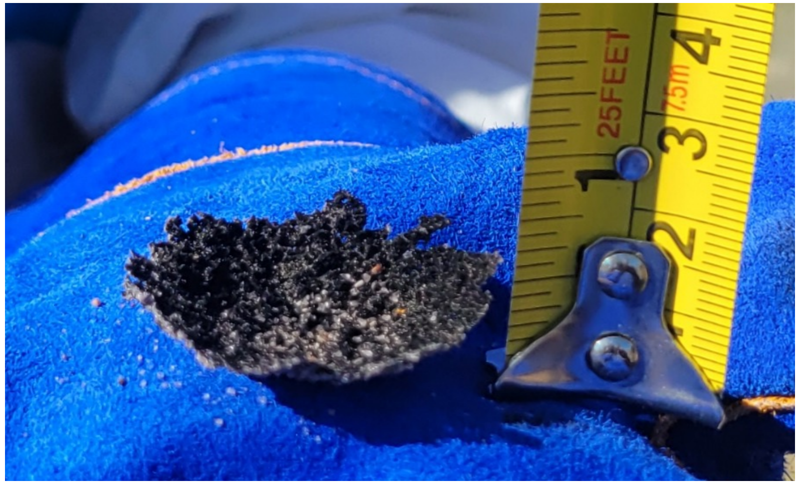
Risk Management – Risk Priority Matrix

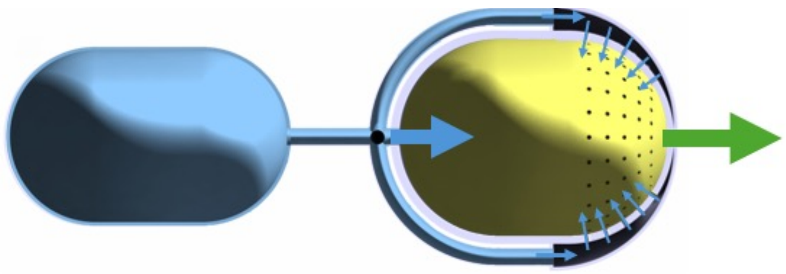
LIKELIHOOD					
5					
4		7			2,5
3		9	14	6,17	1,3
2			15		11
1	8		16	10,12,13	4
	1	2	3	4	5
	CONSEQUENCES				

Verification and Validation

Risk Management – Risks and Mitigations

1	Additive conglomeration performance	→ Experimentation
5	Additive melting properties	→ Experimentation
11	Deployment efficiency	→ Optimization
2	System mass requirements	→ Optimization
8	Additive health hazards	→ Procedure





Agenda

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Budget

Cost Estimations

- PCEC used to estimate System Cost
- CER formula based on mechanical systems for prior missions
- Assumes deployment system is 200 kg (0.5% lander mass)
- Total Non-Recurring: **$23.3M**; Recurring: **$11.2M**

Cost Phase	FY2015 $M (Direct Output)	FY2024 $M (Inflation-Adjusted)
Non-Recurring	19.6	23.3
Design & Development	7.4	8.7
System Test Hardware	12.3	14.6
Flight Unit	9.4	11.2

Budget

Full Breakdown

- Total Project: **$55M**
- 10 employees
- 50% manufacturing margin
- 30% total cost margin

Mission Phase	Phase A	Phase B	Phase B	Phase C	Phase D	
Year	**FY 1 (2025)**	**FY 2 (2026)**	**FY 3 (2027)**	**FY 4 (2028)**	**FY 5 (2029)**	**Cumulative Total ($K)**
PERSONNEL						
Science Personnel (1)	80	82	82	86	88	419
Engineering Personnel (4)	320	328	328	345	353	1,675
Technicians (1)	60	62	62	65	66	314
Administration Personnel (2)	120	123	123	129	132	628
Project Management (2)	240	246	246	259	265	1,256
Total Salaries	**820**	**841**	**841**	**884**	**905**	**4,292**
Total ERE	**229**	**235**	**235**	**247**	**253**	**1,198**
DIRECT COSTS						
System Cost (from CER)	4,660	4,781	4,902	5,023	5,145	24,512
Manufacturing Margin (50%)	2,330	2,391	2,451	2,512	2,572	12,256
Total Direct Costs	**6,990**	**7,172**	**7,353**	**7,535**	**7,717**	**36,767**
FINAL COST CALCULATIONS						
Total Projected Cost	8,039	8,248	8,430	8,666	8,880	42,263
Total Cost Margin (30%)	2,412	2,474	2,529	2,600	2,664	12,679
Total Project Cost	**10,451**	**10,722**	**10,958**	**11,266**	**11,545**	**54,941**

Timeline

- 5-year Plan
  - 10 months of margin
  - Additional testing
    - Full scale verification
  - Major reviews
    - NASA SEH 3.0 (Hirshorn, 2016)

Project Start:
Jan 2025
- NASA SEH 3.0

Phase A Reviews:
Dec 2025 – Feb 2026
- SRR
- SDR

Phase B Reviews:
Mar 2027 – May 2027
- BPP
- PDR

Phase C Reviews:
Aug 2028 – Oct 2028
- CDR
- SIR

Phase D Reviews:
Aug 2029 – Oct 2029
- ORR
- FRR

Agenda


Introduction
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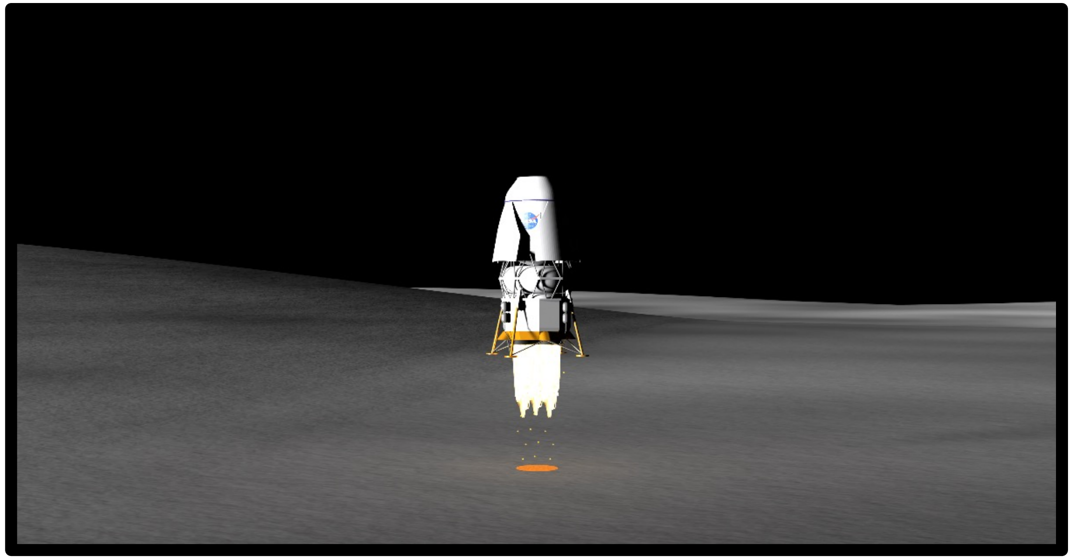
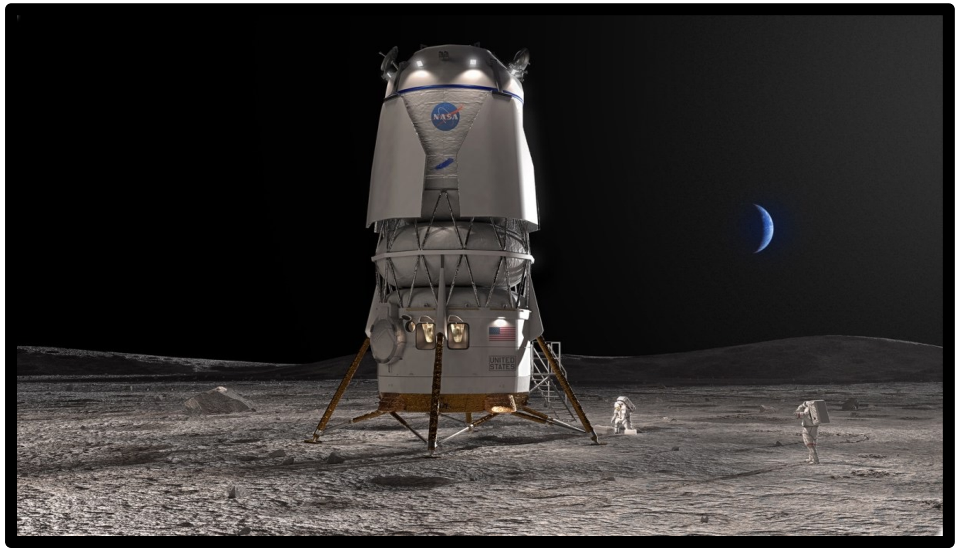
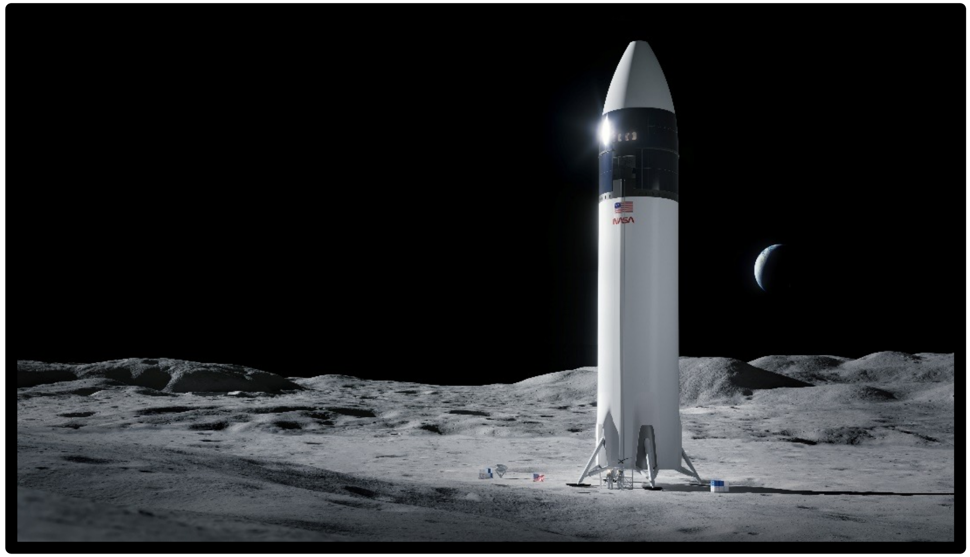
Conclusion

- Tests and simulations support PARSEC additive solution at-scale
- Further testing and simulations at-scale required
- Confidence in solution
- Effective, scalable solution with great promise





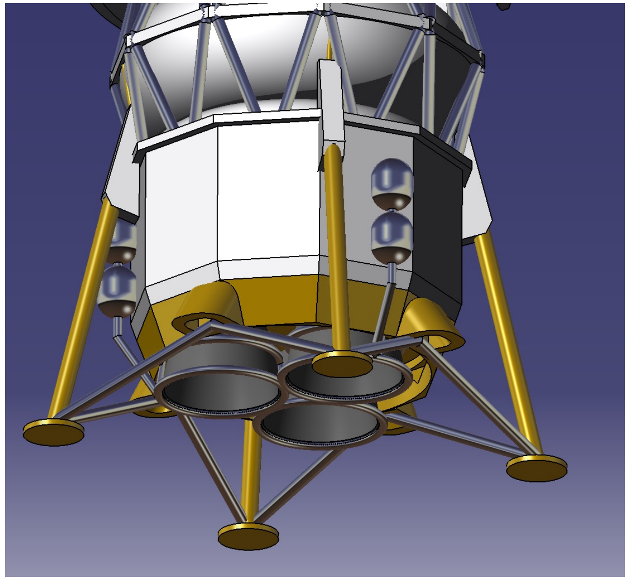
Blue Moon Lander Concept Image (Blue Origin, 2023)

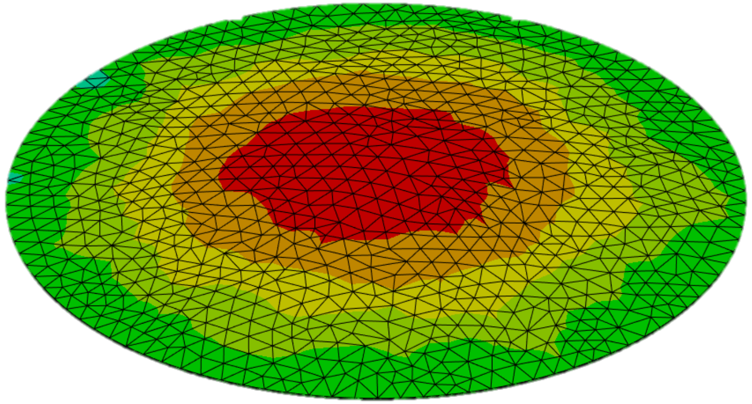


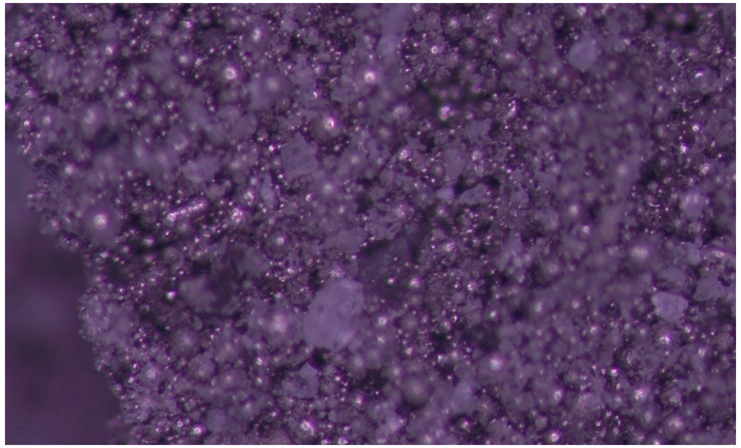
Starship Human Lander System Concept Image (SpaceX, 2024)

Next Steps

- Future Experimentation is necessary to determine feasibility
  - Scaling, environment, shapes and sizes, additive types
- Implementation







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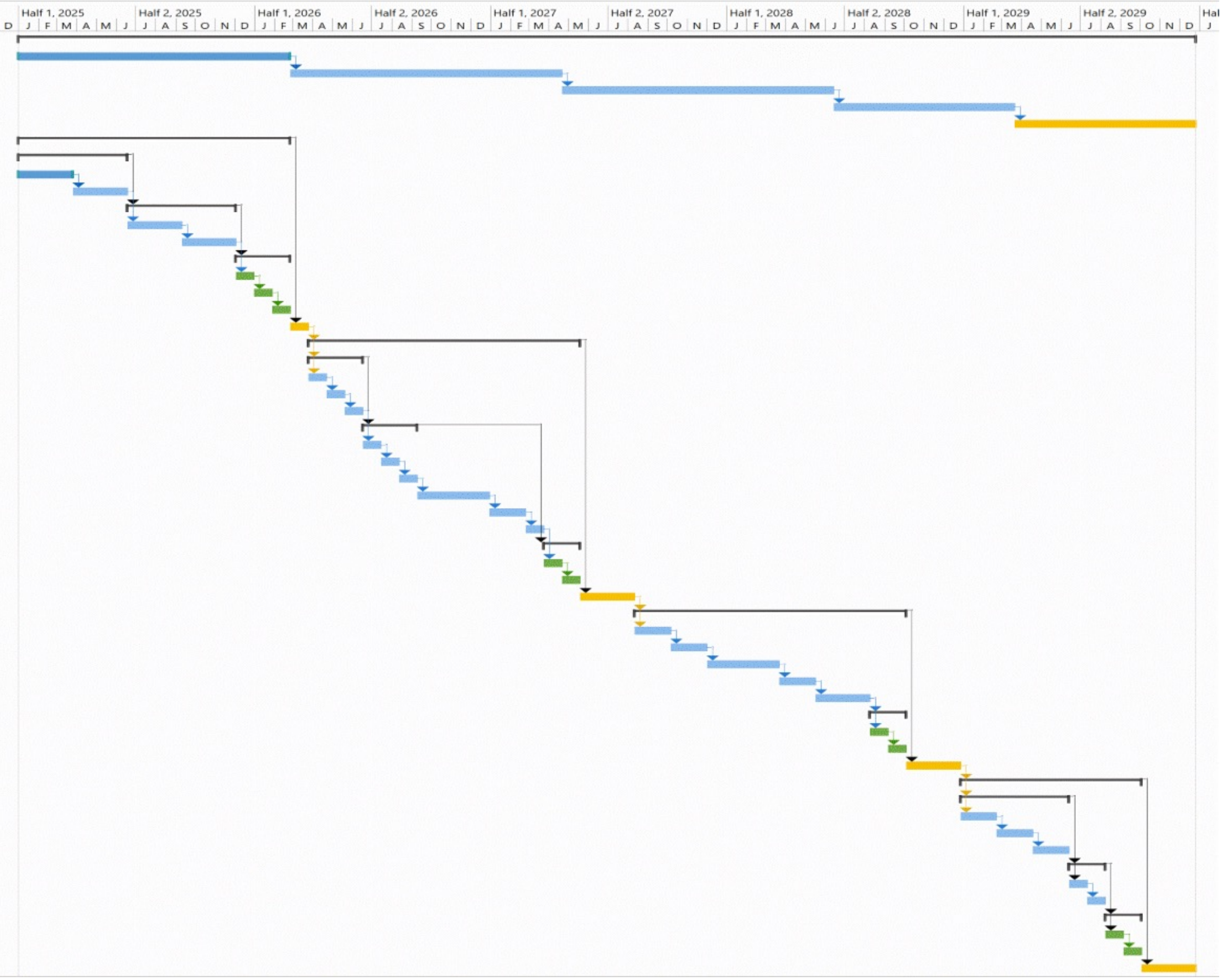
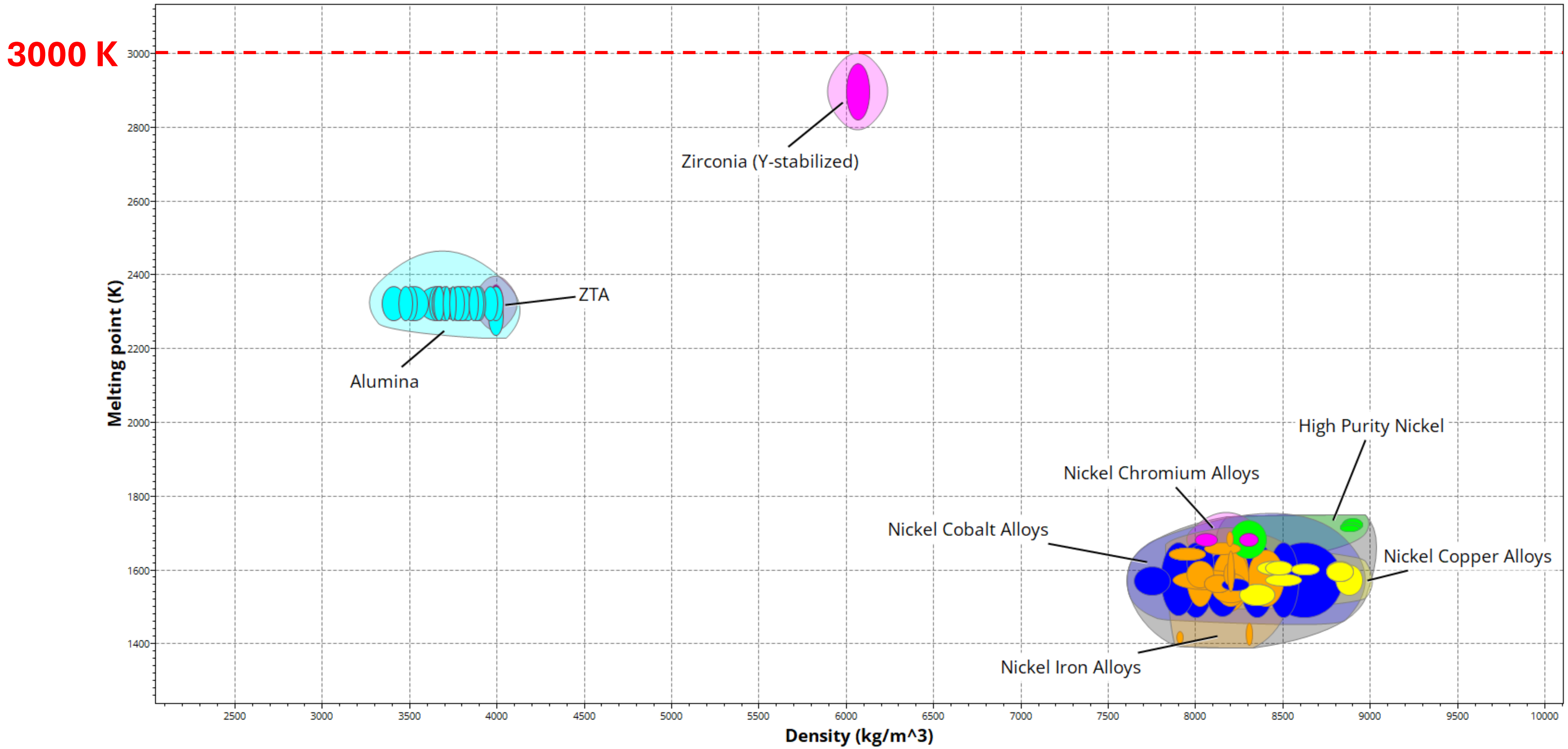
Appendix

Project Timeline

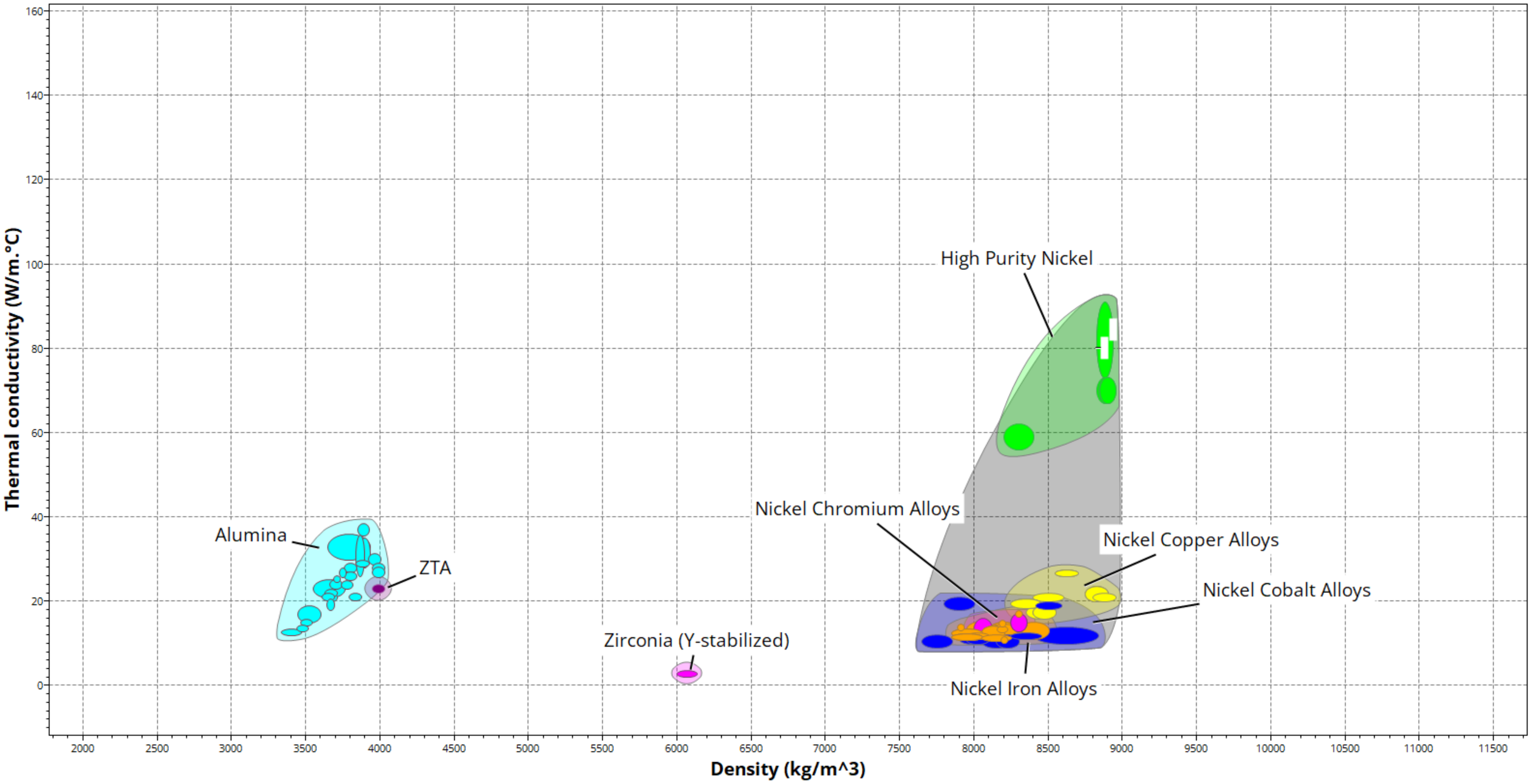
Task Name	Duration	Start
PARSEC Overview	1300 days	1/1/25
Phase A	300 days	1/1/25
Phase B	300 days	2/25/26
Phase C	300 days	4/21/27
Phase D	200 days	6/14/28
Total Dedicated Margin	10 mons	3/21/29
Phase A	300 days	1/1/25
Test Candidate Additives	120 days	1/1/25
Particle Structure Test	3 mons	1/1/25
Particle Size Test	3 mons	3/26/25
Test Deployer Variations	120 days	6/18/25
Injection Angle Test	3 mons	6/18/25
Injection Velocity Test	3 mons	9/10/25
Reviews	60 days	12/3/25
SRR	1 mon	12/3/25
SDR	1 mon	12/31/25
PPP	1 mon	1/28/26
Phase A Margin	1 mon	2/25/26
Phase B	300 days	3/25/26
Determine Additive	60 days	3/25/26
Additive Chemical	1 mon	3/25/26
Additive Particle Size	1 mon	4/22/26
Additive Particle Shape	1 mon	5/20/26
Develop Deployer	60 days	6/17/26
Deployer Nozzle Size	1 mon	6/17/26
Deployer Flow Rate	1 mon	7/15/26
Deployer Angle	1 mon	8/12/26
System Tests	4 mons	9/9/26
Modifications	2 mons	12/30/26
Concept of Operations	1 mon	2/24/27
Reviews	40 days	3/24/27
BPP	1 mon	3/24/27
PDR	1 mon	4/21/27
Phase B Margin	3 mons	5/19/27
Phase C	300 days	8/11/27
Finalise Additive	2 mons	8/11/27
Finalize Deployer	2 mons	10/6/27
Integrated Test	4 mons	12/1/27
Finalize Con-Ops	2 mons	3/22/28
Manufacturing Process	3 mons	5/17/28
Reviews	40 days	8/9/28
CDR	1 mon	8/9/28
SIR	1 mon	9/6/28
Phase C Margin	3 mons	10/4/28
Phase D	200 days	12/27/28
Fully Integration Testing	120 days	12/27/28
Thermal Testing	2 mons	12/27/28
Vacuum Testing	2 mons	2/21/29
Viberations Testing	2 mons	4/18/29
Prepare Launch Operations	40 days	6/13/29
Prepare Operations	1 mon	6/13/29
Prepare Ground Sopport	1 mon	7/11/29
Reviews	40 days	8/8/29
ORR	1 mon	8/8/29
FRR	1 mon	9/5/29
Phase D Margin	3 mons	10/3/29



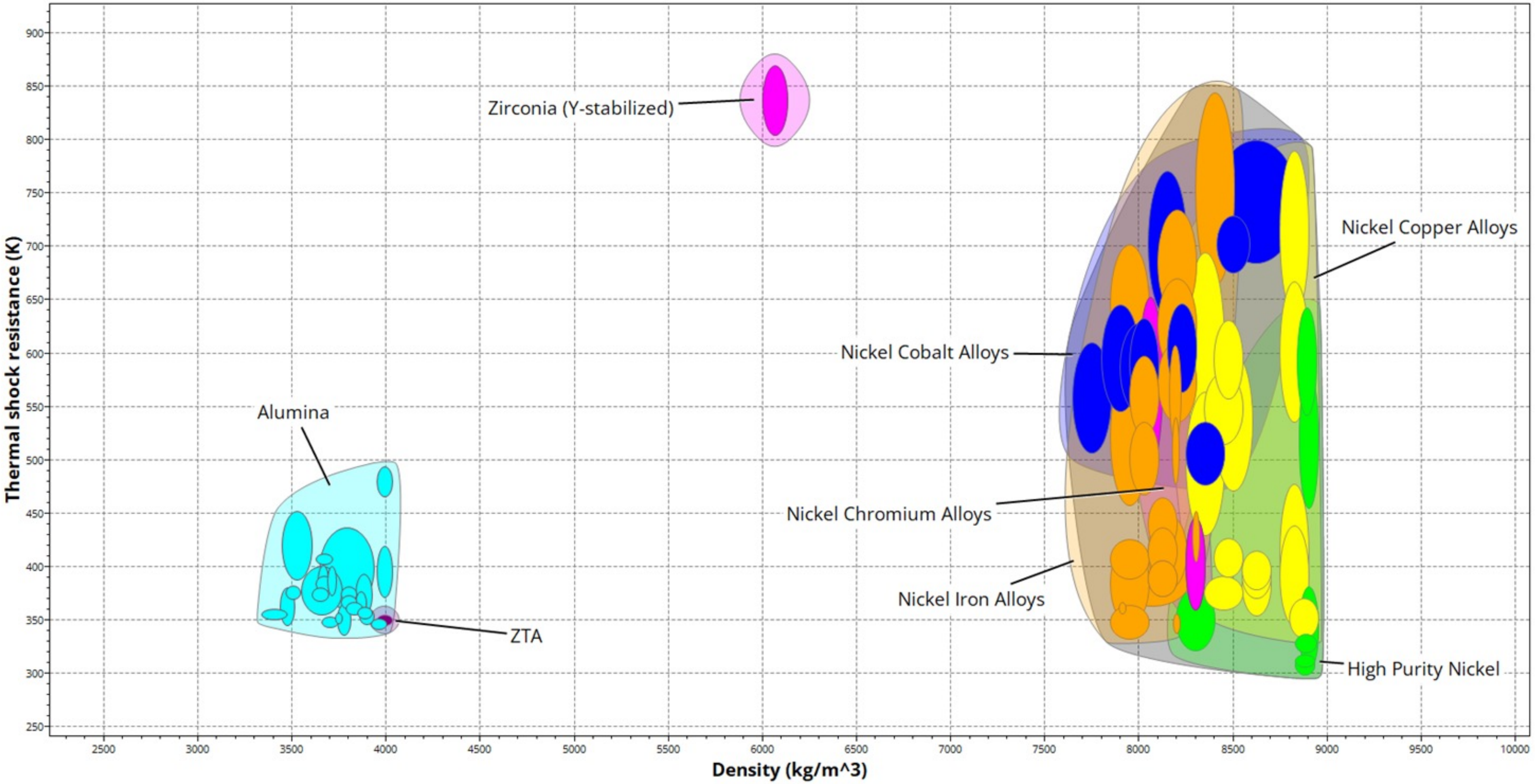
Additives – Melting Point



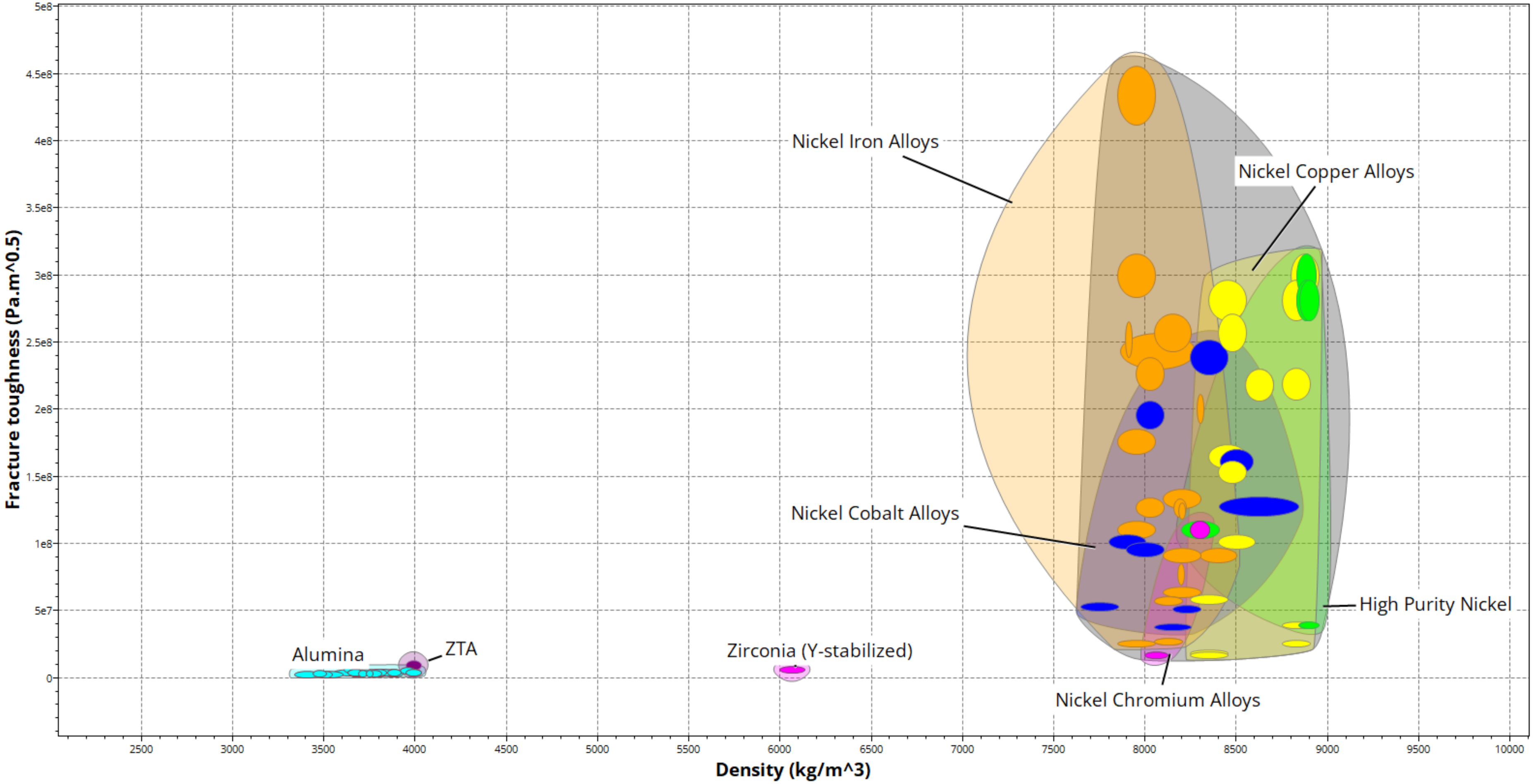
Additives – Thermal Conductivity



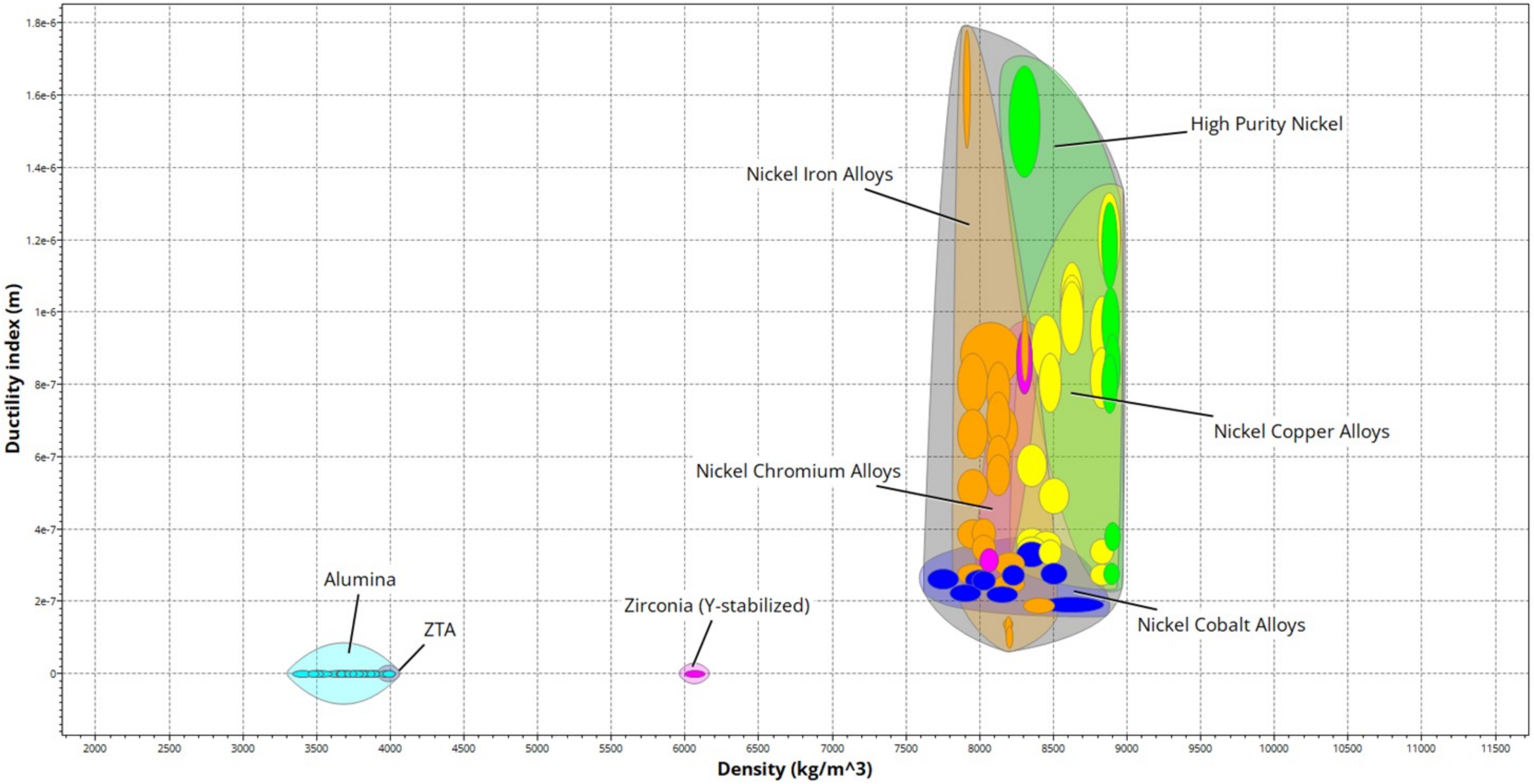
Additives – Thermal Shock Resistance



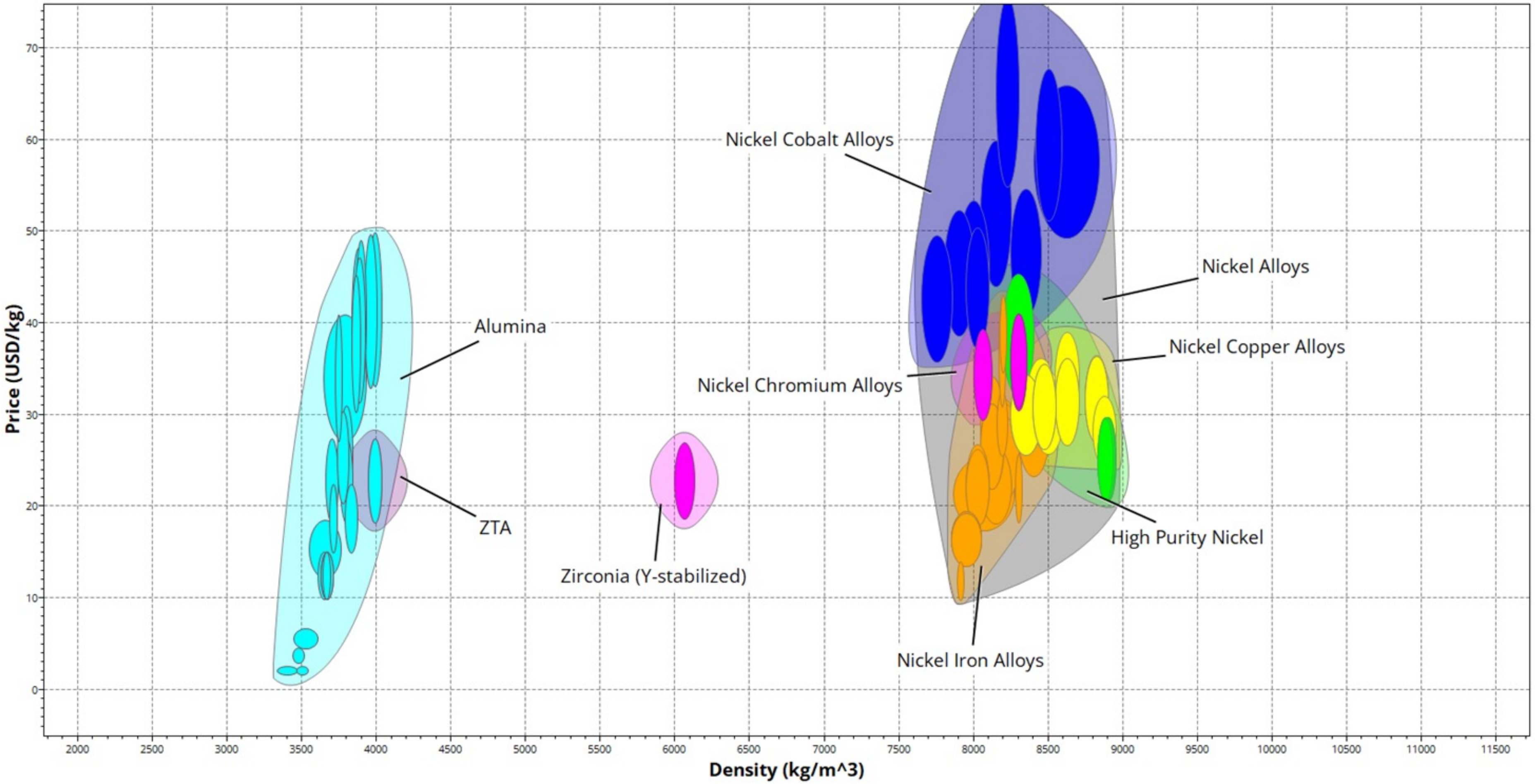
Additives – Fracture Toughness



Additives – Ductility Index



Additives – Price

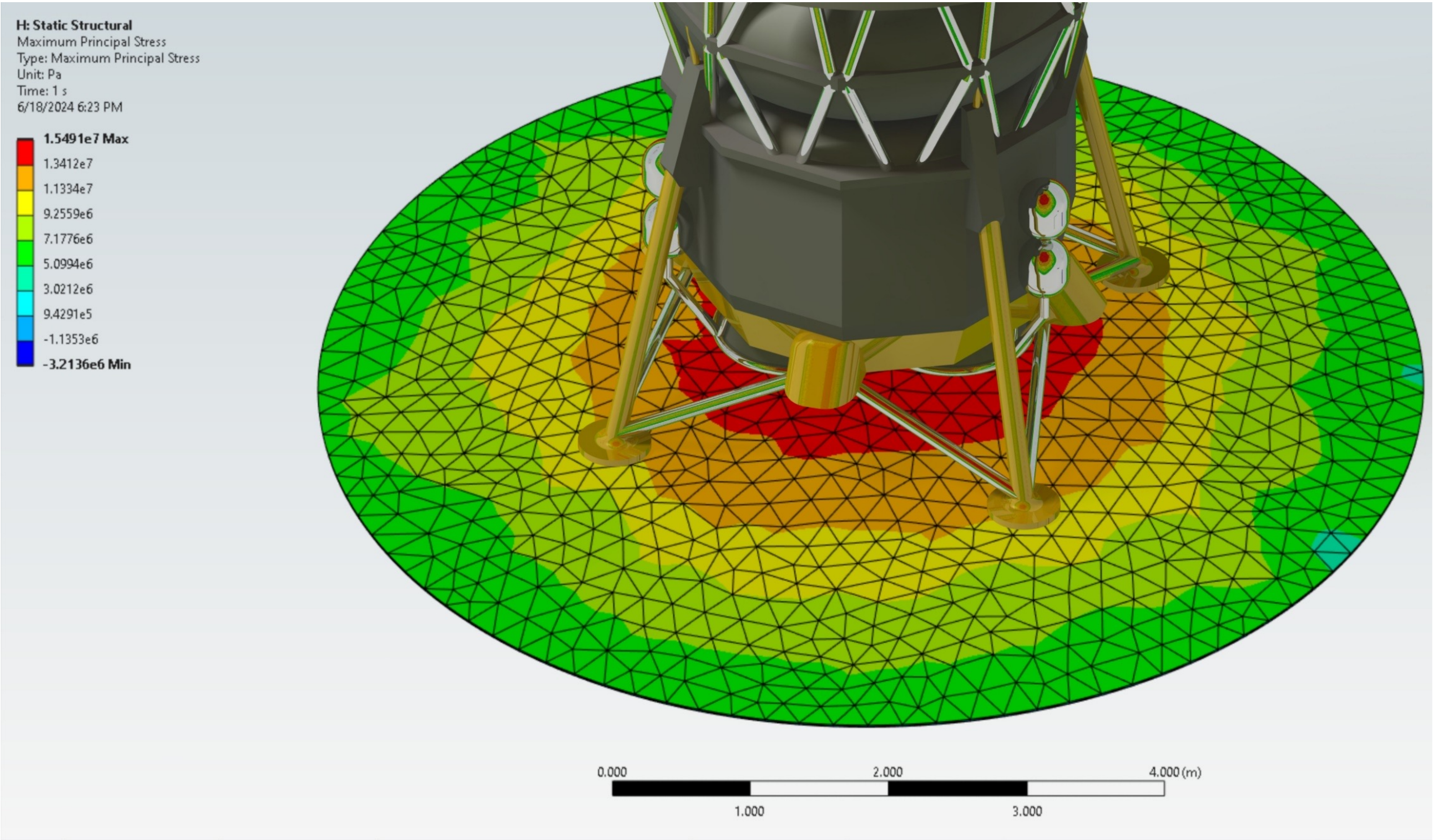


Deployment System		Scores		Trades								
Criteria	Mandatory? (Y=1/ N=0)	Weight	Scale	Thermite Microcapsules*	Auger	Impeller	Extra Engine	Cannon	Magazine	Fluidization	COPVs *	Ionization Fluidizatoin *
Modifications Required	1	15%	1-3	3	2	2	1	2	2	2	2	2
Plume Survivability (Temp, Press.)	1	20%	1-3	1.5	3	3	3	2	2.5	3	3	3
Danger to Vessel	1	10%	1-3	1.5	3	2.5	1	3	2.5	3	3	3
Transit/Weight	1	10%	1-3	3	2	1.5	1	3	2	2.5	2.5	2.5
TRL	0	10%	1-3	2	2	3	3	2	1	3	3	3
Testability	0	15%	1-3	2	1.5	3	1	3	1	3	3	3
Effectiveness	1	10%	1-3	2.5	1	3	1.5	1.75	1	3	3	3
Resource Consumption	1	10%	1-3	3	1.5	1.5	1.5	3	3	2.5	2.5	2
Weighted Total %		100%		75%	69%	83%	57%	81%	63%	92%	92%	90%

*Can be integrated with other deployment systems

Plume Additive		Scores		Trades					
Criteria	Mandatory? (Y=1/ N=0)	Weight	Scale	Ceramics	Thermoplastics	SiAlON Thermal Spray	Liquid Nitrogen	Lotus Leaf	Acids
Safety/non-toxic	1	5%	1-3	3	3	3	3	3	2
Plume Survivability (Temp, Press.)	1	20%	1-3	3	1.5	3	1	2	2
Lunar Environment Survivability	1	20%	1-3	3	2	3	1	3	2
Transit/Deployment	0	10%	1-3	3	3	2.75	1.5	3	1
TRL	0	10%	1-3	2	2	1.25	3	3	1
Testability	0	15%	1-3	2	2.5	2	3	3	1.5
Effectiveness	0	10%	1-3	2.5	1.5	2	1.75	1.5	1.5
Accessibility of Additive	0	10%	1-3	3	3	3	3	1	3
Weighted Total %		100%		90%	73%	85%	64%	82%	59%

PARSEC on Blue Moon Rendered on Landing Pad Simulation



PARSEC on Blue Moon Render