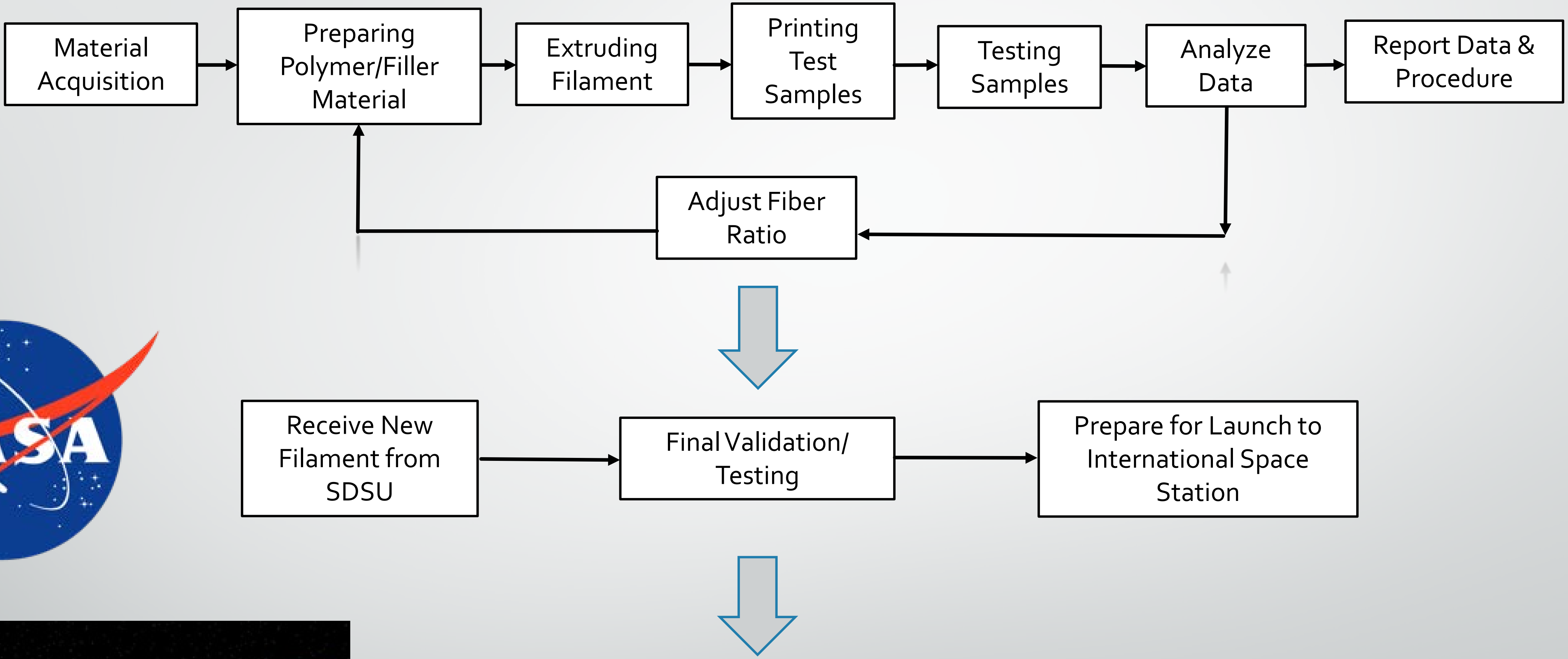
NASA X-Hab SAR/ORR

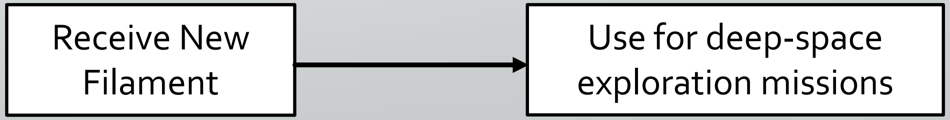
Adrian Weerakkody, Brad Drake, Easton Schuster, Mikala Fjerstad, Natalie Coughlin, and Tyler Waege

Agenda

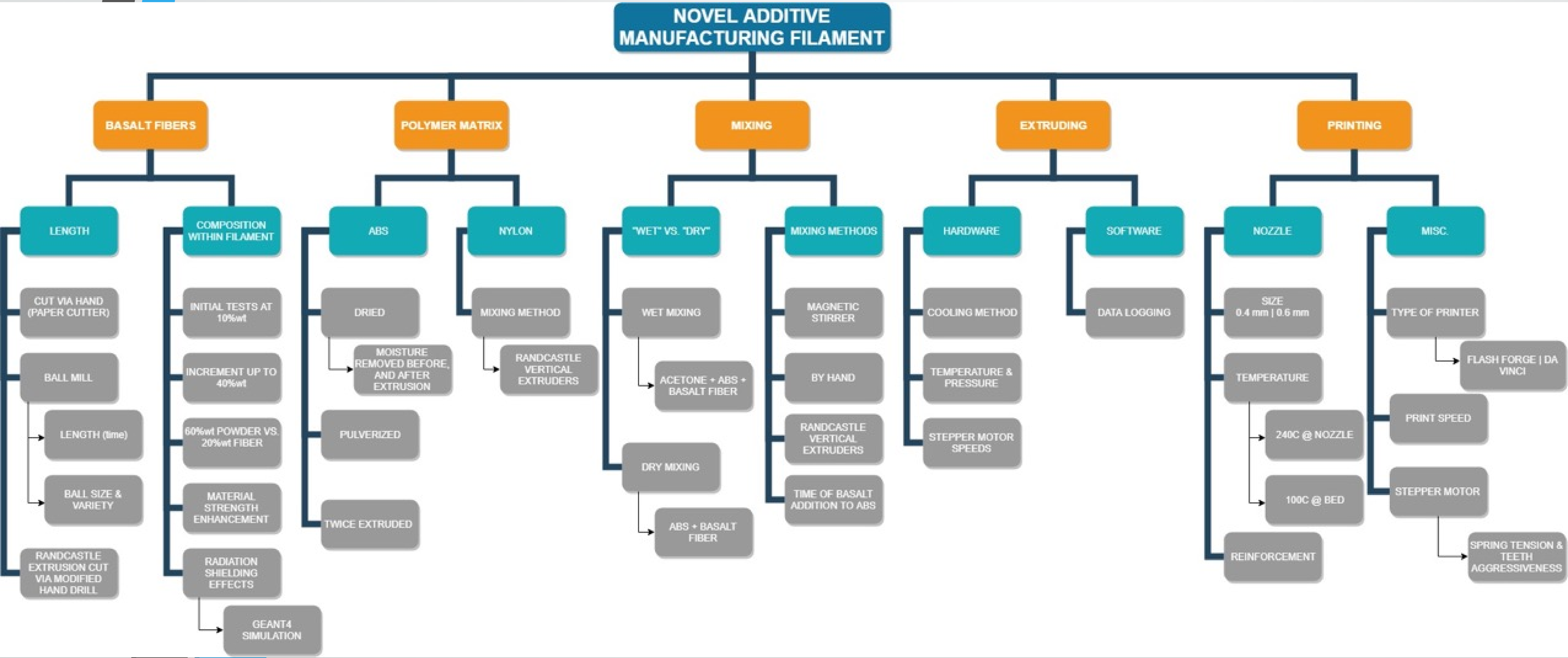
- Project Overview
- Updates
  - Destructive Testing
  - Non-Destructive Testing
- SDSU Engineering Expo
- Publication Status
- Expected Deliverables
- Student Future Endeavors

Finalized concepts of operations

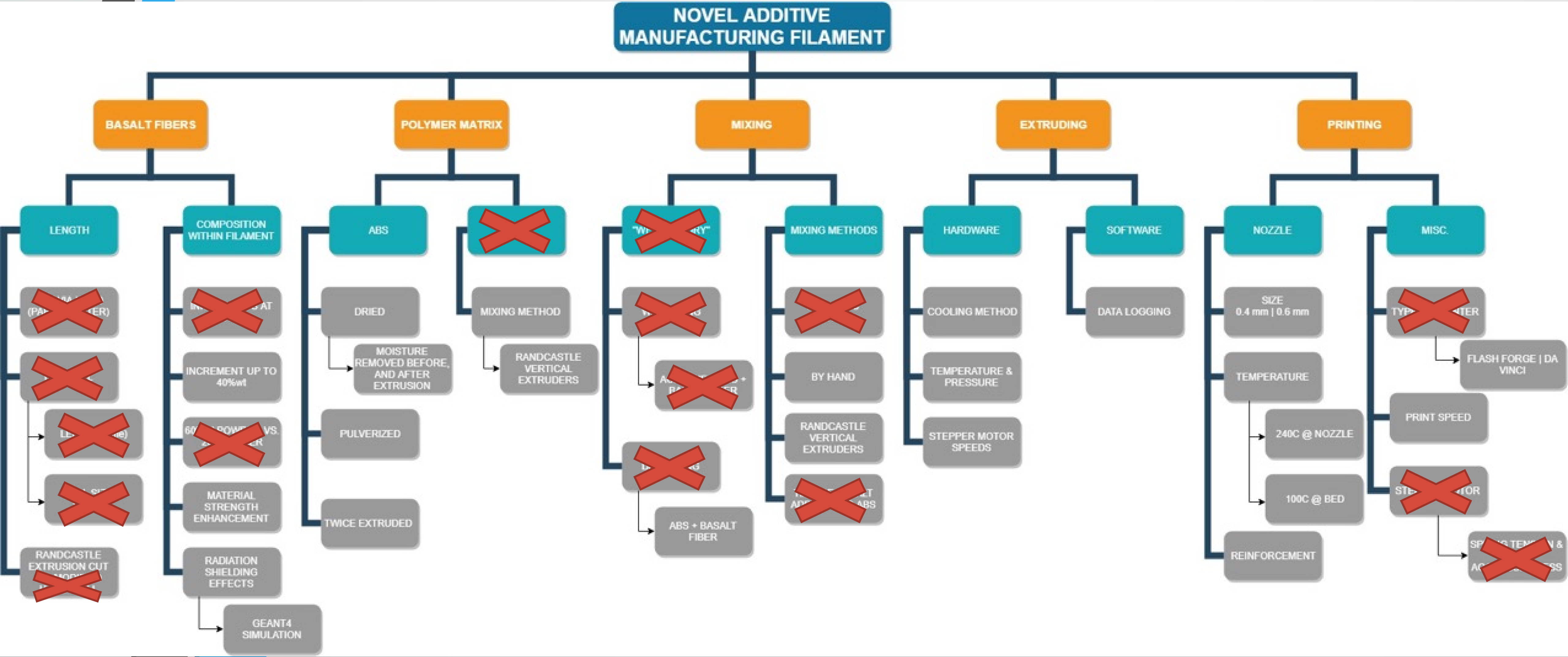




Top Level Requirements & Flow down



Top Level Requirements & Flow down



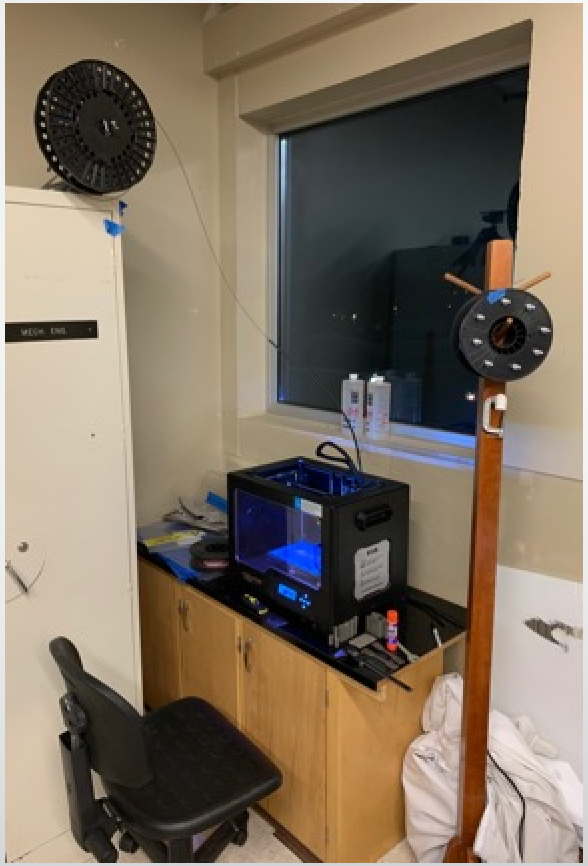
Finalized System of Operations

- Mixing
  - Randcastle vertical extruder
- Pelletizing
  - Industrial Shredder
- Extruding
  - SDSU LEADER Lab Extruder
- Printing
  - Flash Forge
- Testing:
  - Compression Testing (ASTM D695/D6641)
  - Tensile Testing (ASTM D638)
  - Flexural Testing (ASTM D790)
  - Fatigue (Axial/Flexural) Testing (ASTM D7791/D774)
  - Izod Impact Testing (ASTM D256)

Risks in Manufacturing

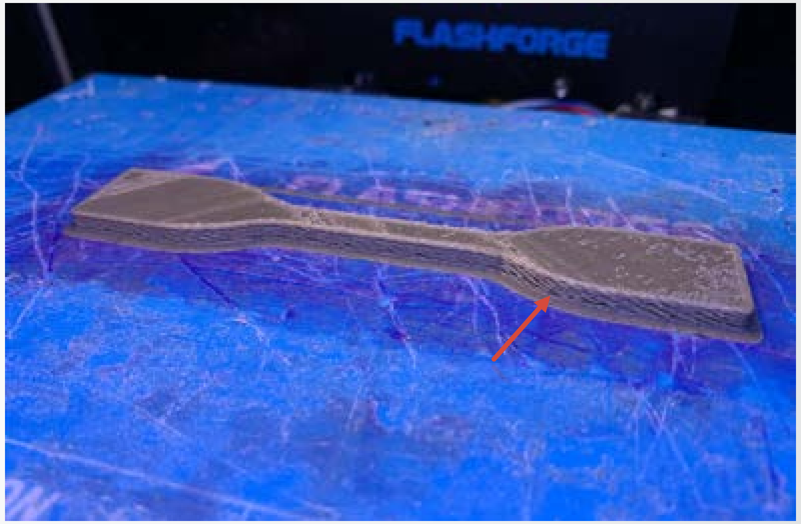
Spooling

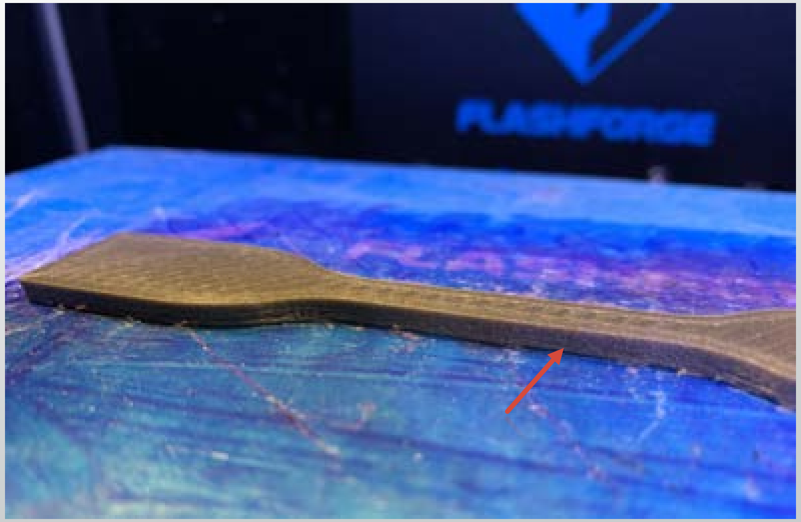
- Material Breaking on Regular Spool with small inner diameter
  - Solution: replace with larger spool (Stratasys spool)
- Material on Spool Breaking while Fed to 3D Printer
  - Solution: suspend spool above 3D printer to make path from spool to extruder more straight vs tight bend radius from back of machine over the top and back down to the extruder



Printing

- Rough, irregular filament
  - Effects: nozzle plugged up and irregular flow rate
  - Solution: adjust spooling setup to keep filament in better condition
- Poor Build Plate Adhesion
  - Effects: part cannot print if the first layer does not adhere properly
  - Solution: clean build plate, ABS/Acetone mixture
- Poor Final Print Quality
  - Effects: parts had poor perimeter finish leading to compromised parts
  - Solution: adjust coding in slicer software to call for slower travel speeds and set proper nozzle dimension



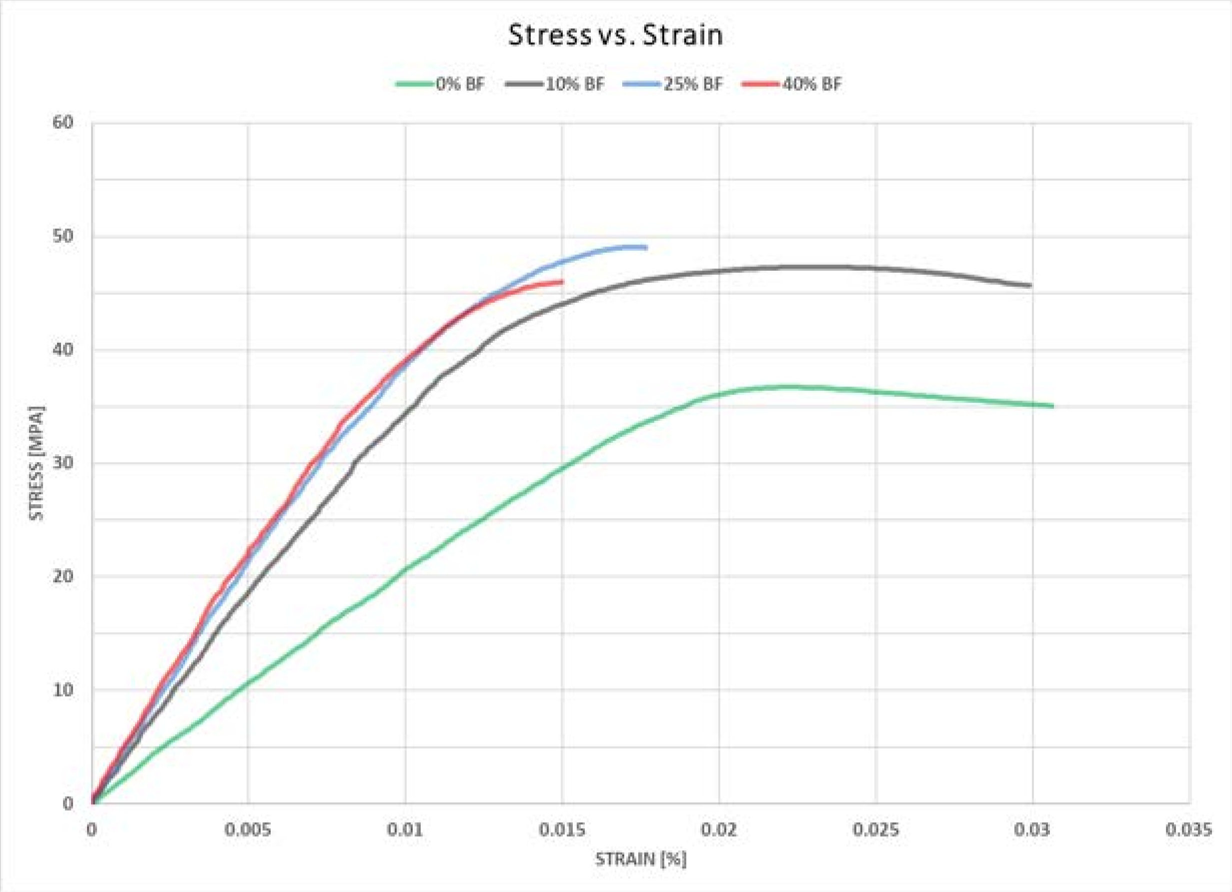


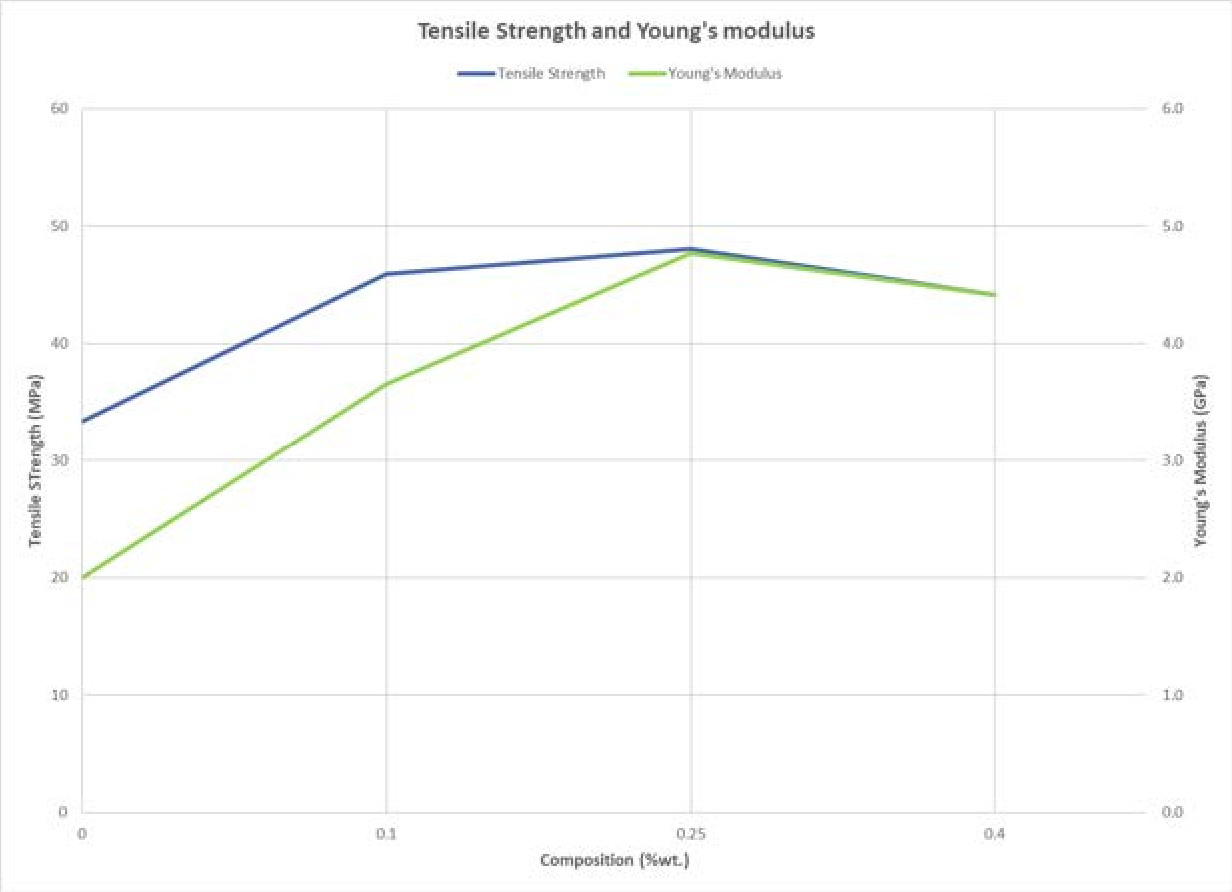
Destructive Testing and Results

Mechanical Properties

	Tensile Strength (MPa)	Young's Modulus (GPa)	Yield Strength (MPa)	Max Elongation (%)	Flexural Strength (MPa)
Commercial ABS	32-42	1.92-1.95	13-65	10	60 -73
ABS	33.41 ± 7.38	2.00 ± 0.36	32.07 ± 7.84	9.97 ± 0.90	56.94 ± 1.24
ABS & 10% BF	45.92 ± 2.06	3.66 ± 0.24	40.36 ± 1.90	2.82 ± 0.15	67.30 ± 1.69
ABS & 25% BF	48.07 ± 6.53	4.77 ± 1.48	44.03 ± 6.06	1.48 ± 0.46	66.95 ± 3.79
ABS & 40% BF	44.19 ± 2.7	4.41 ± 0.70	41.16 ± 2.63	1.50 ± 0.30	60.69 ± 2.56

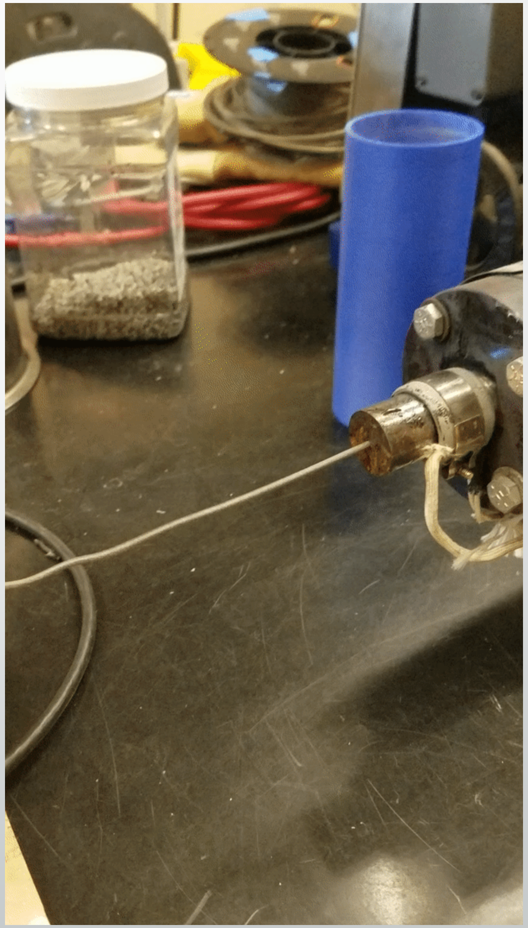
Mechanical Properties

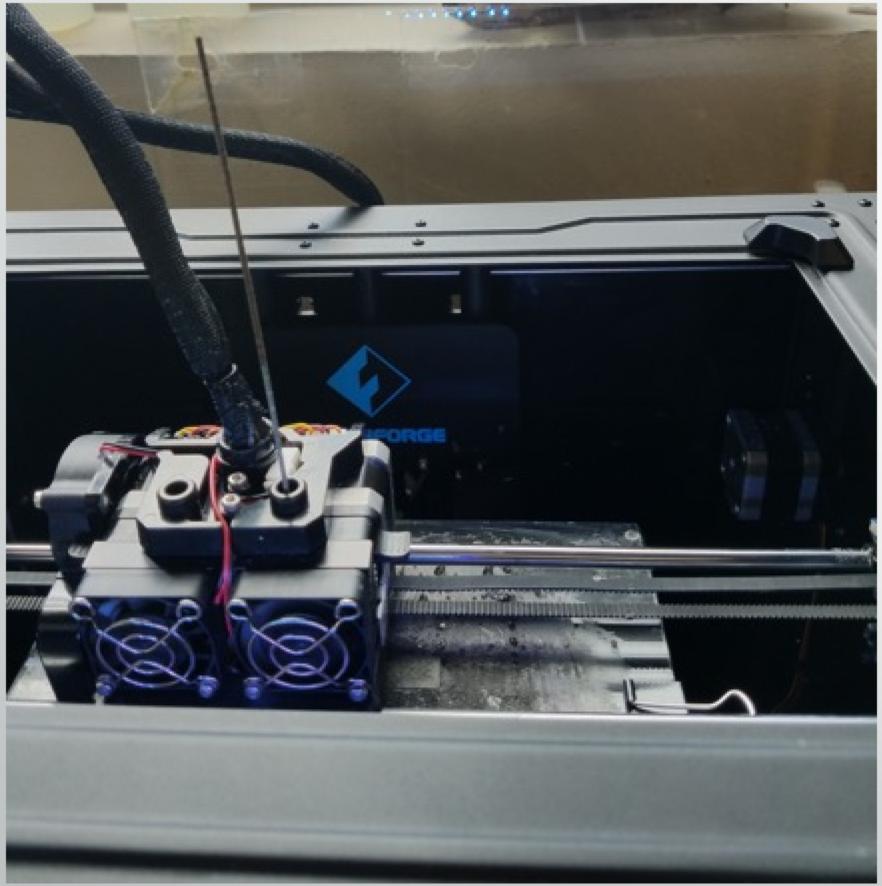


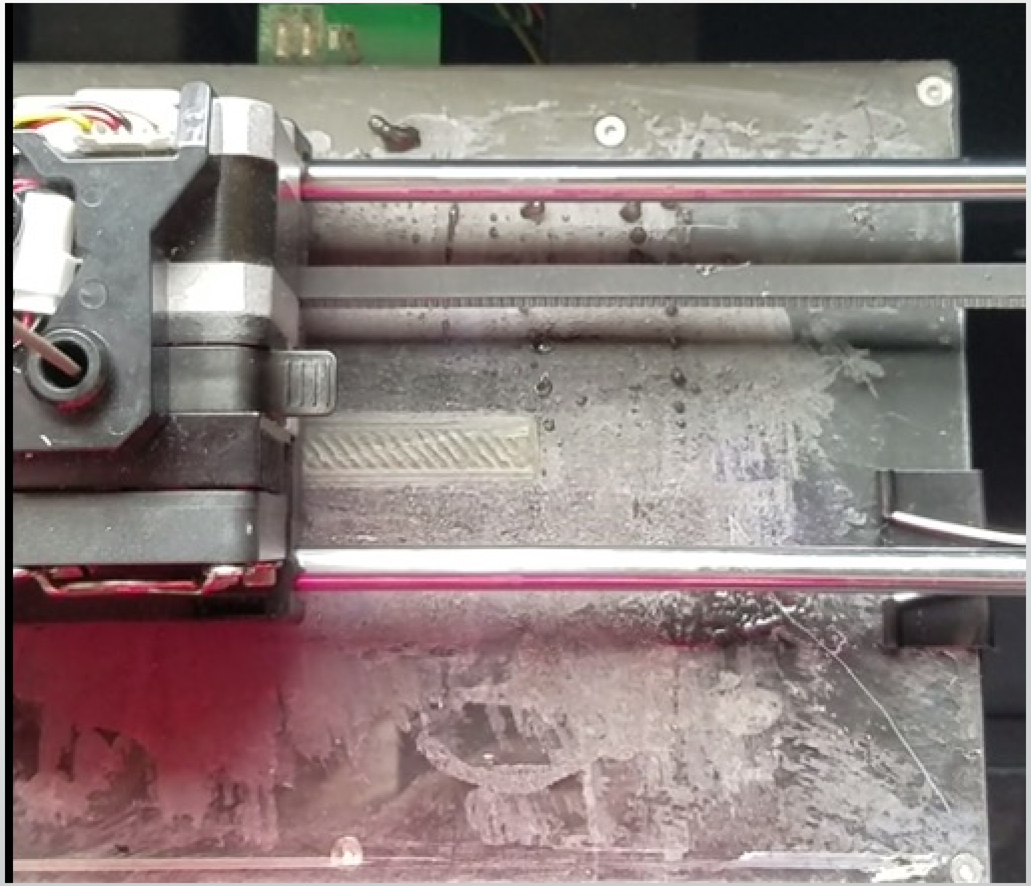


60%wt. Proof of Concept

- We wanted to achieve a material with basalt comprising the majority of the material
- Issues:
  - Tension in the extrusion line pulls material apart
  - Bending radius
- Results:
  - With appropriate dimensions, 60%wt. can be printed!

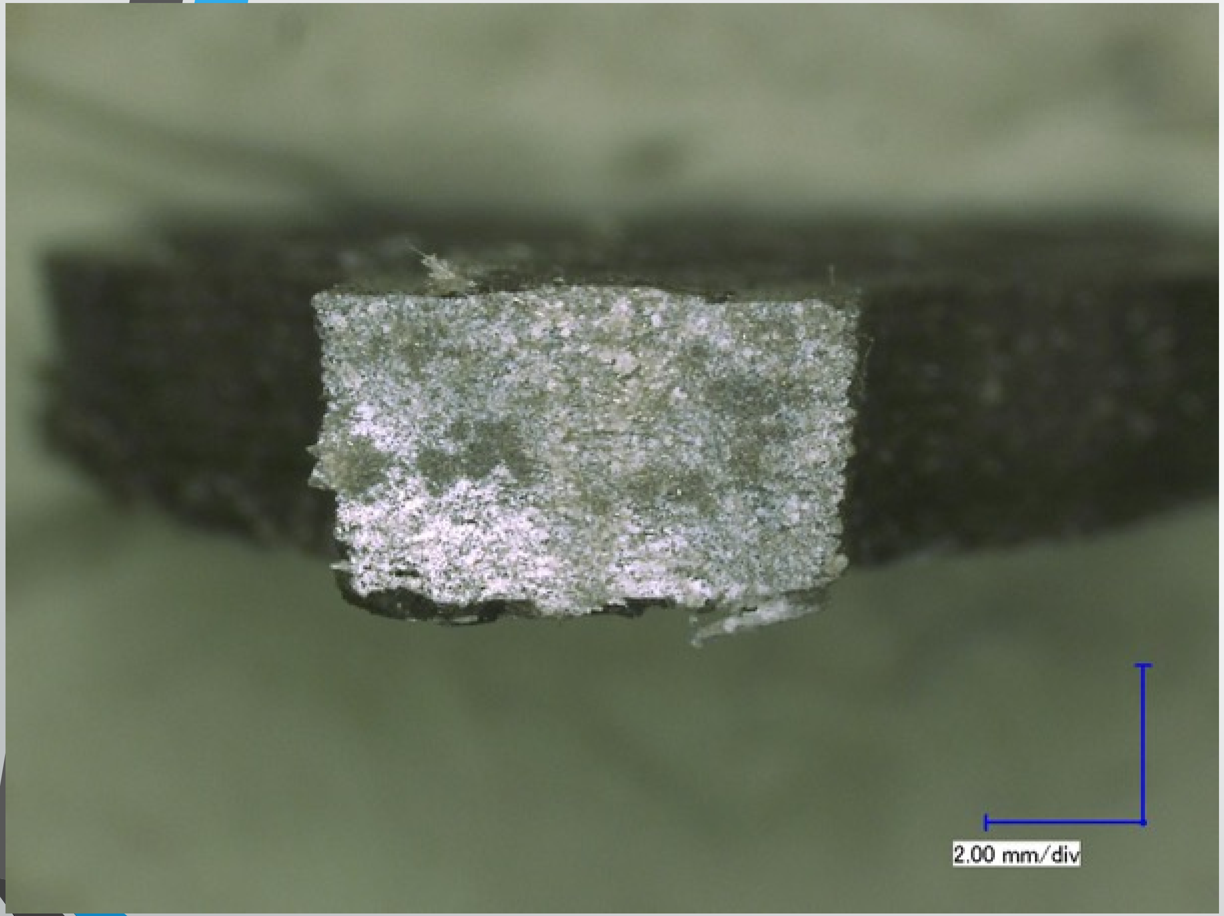




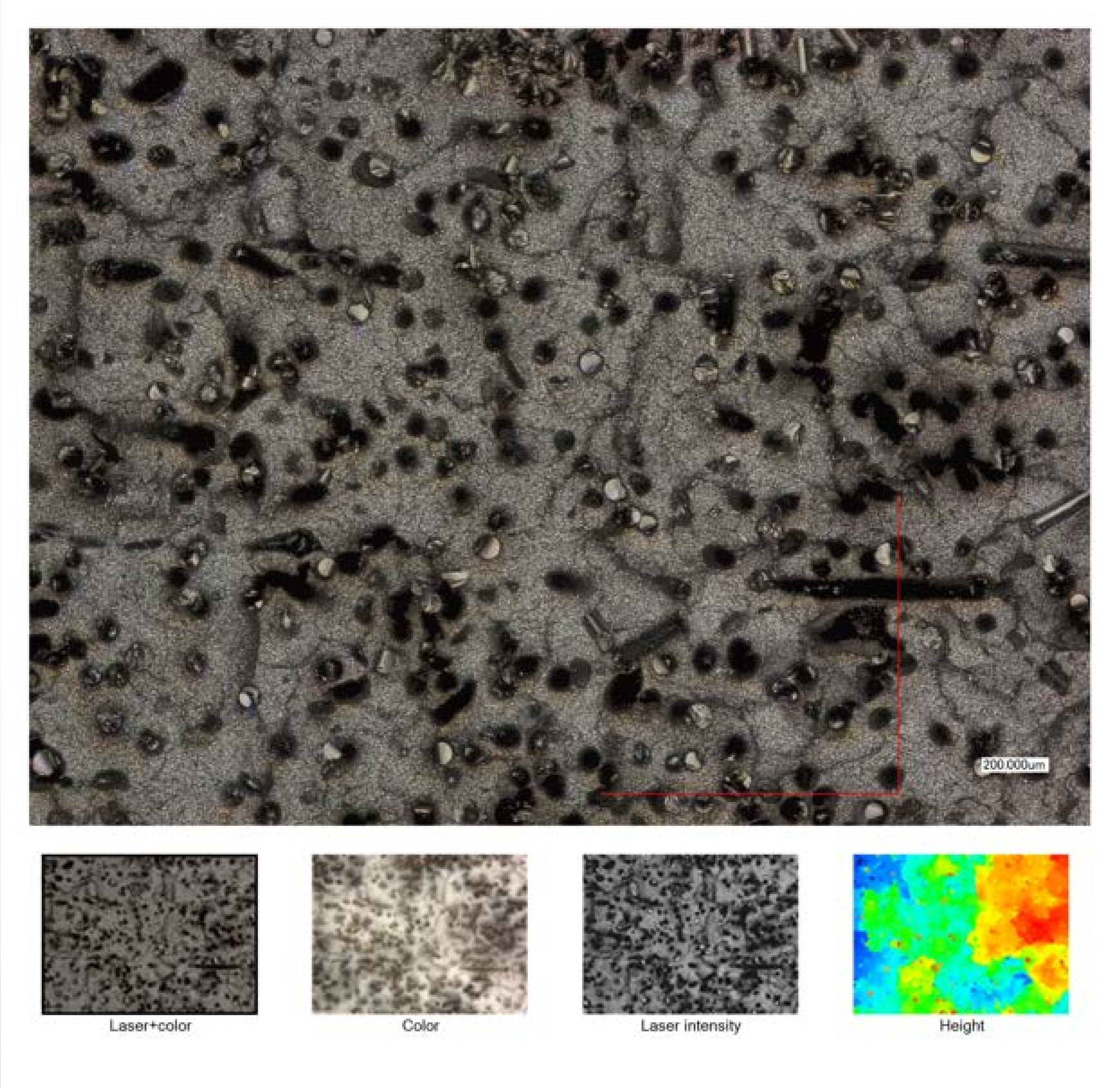


Non-Destructive Testing

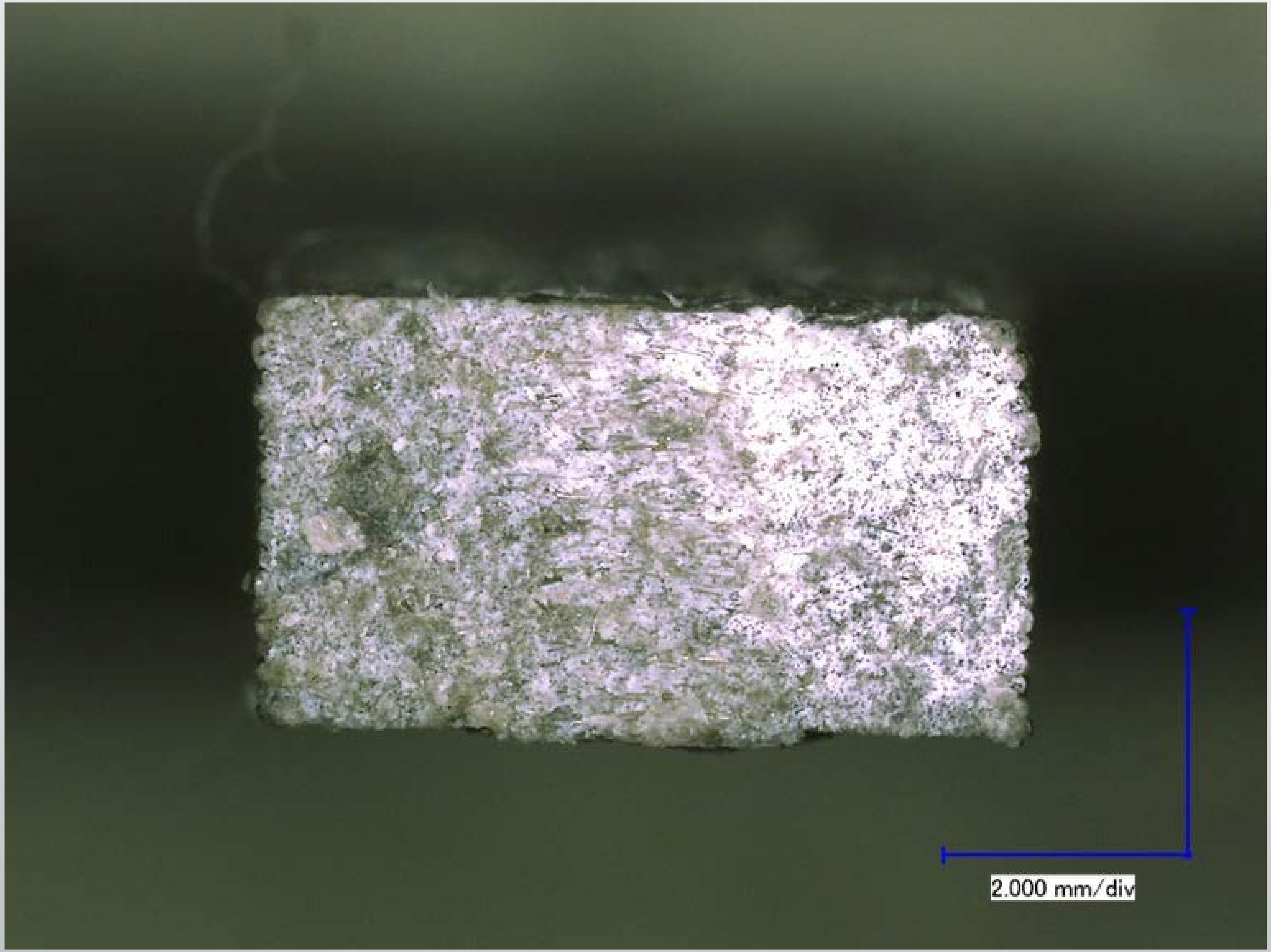
Tensile Sample (40% x100)



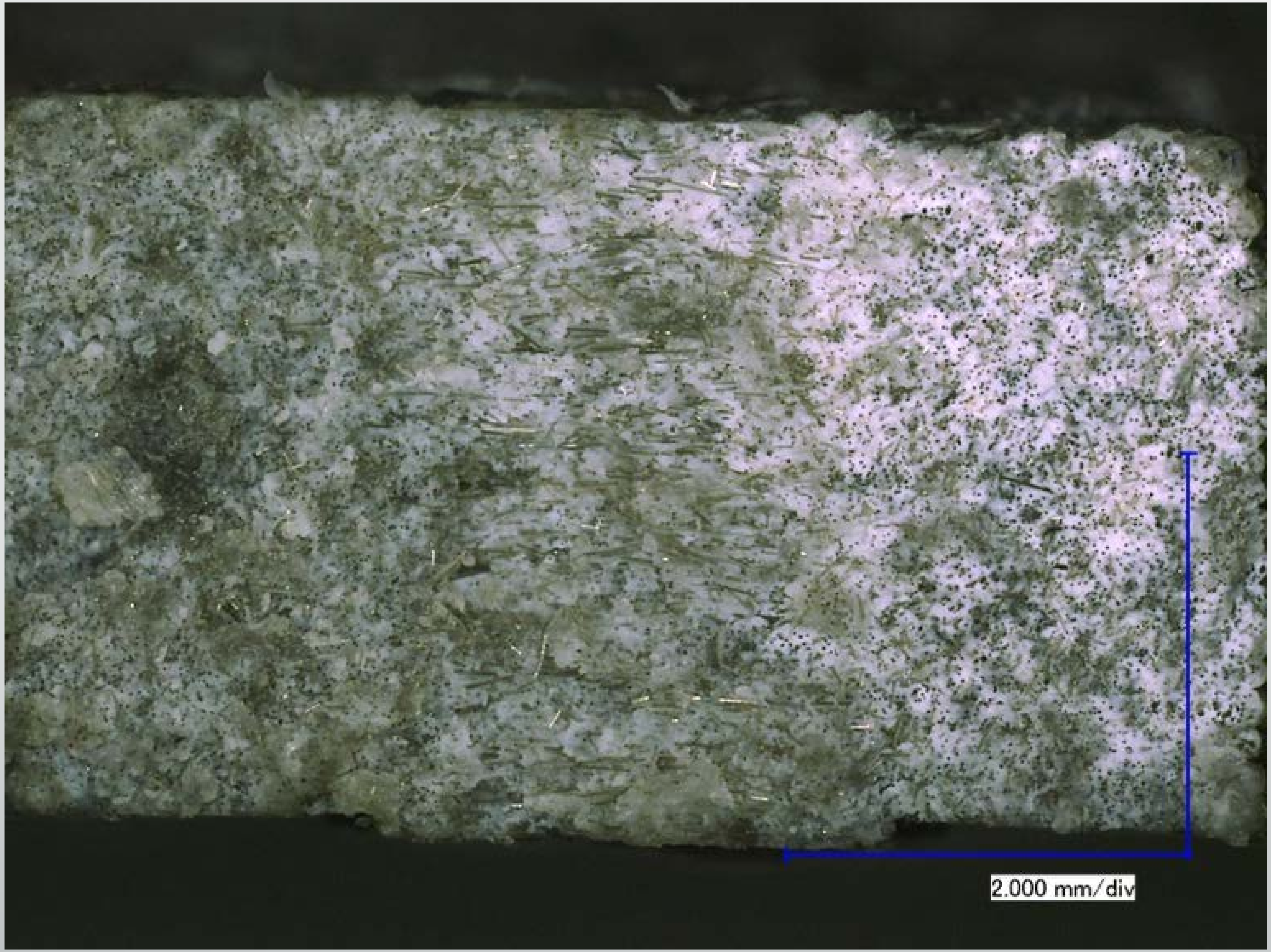
ABS & 40% BF



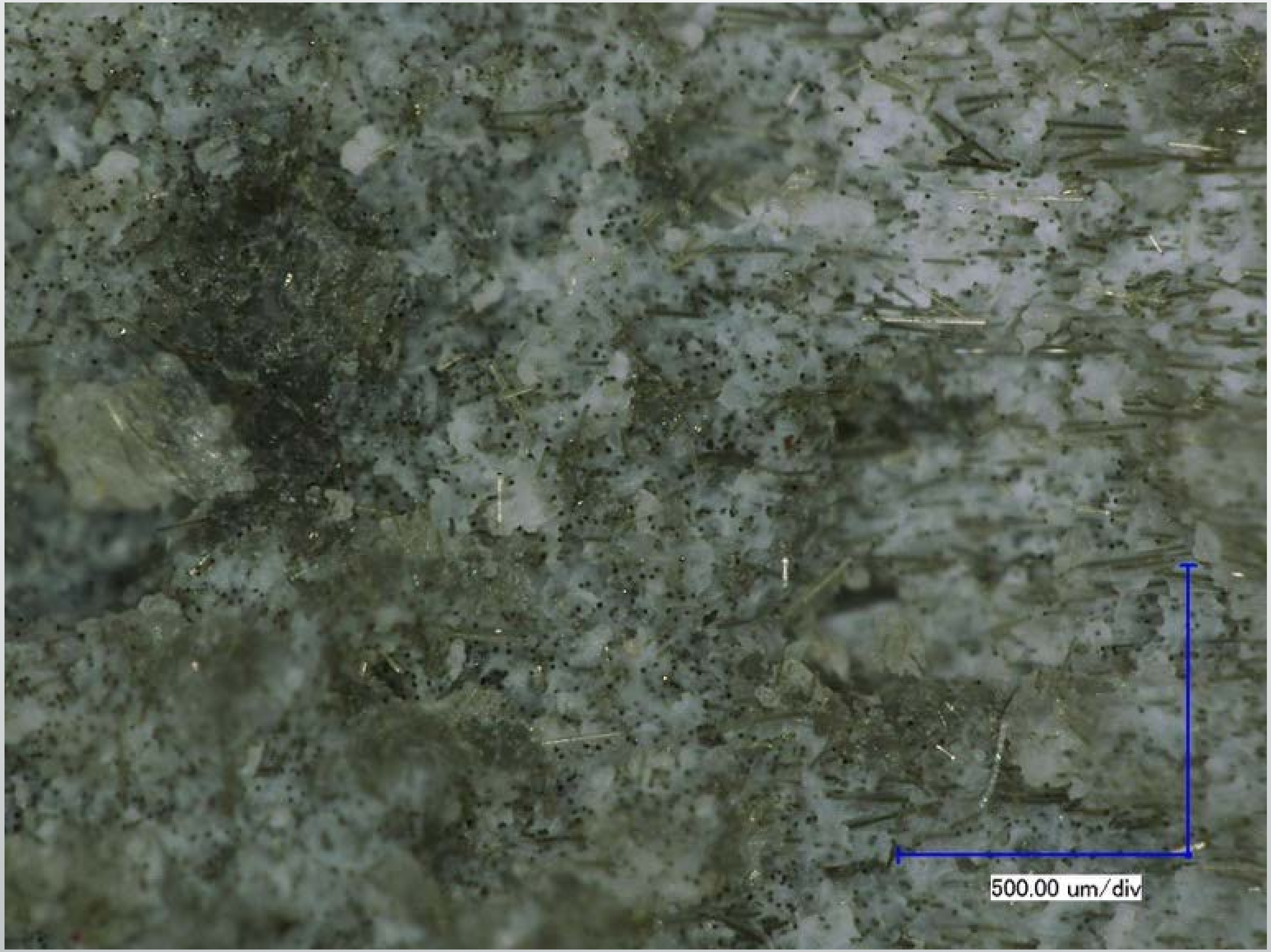
ABS & 40+% BF via laser microscope



25wt_x30

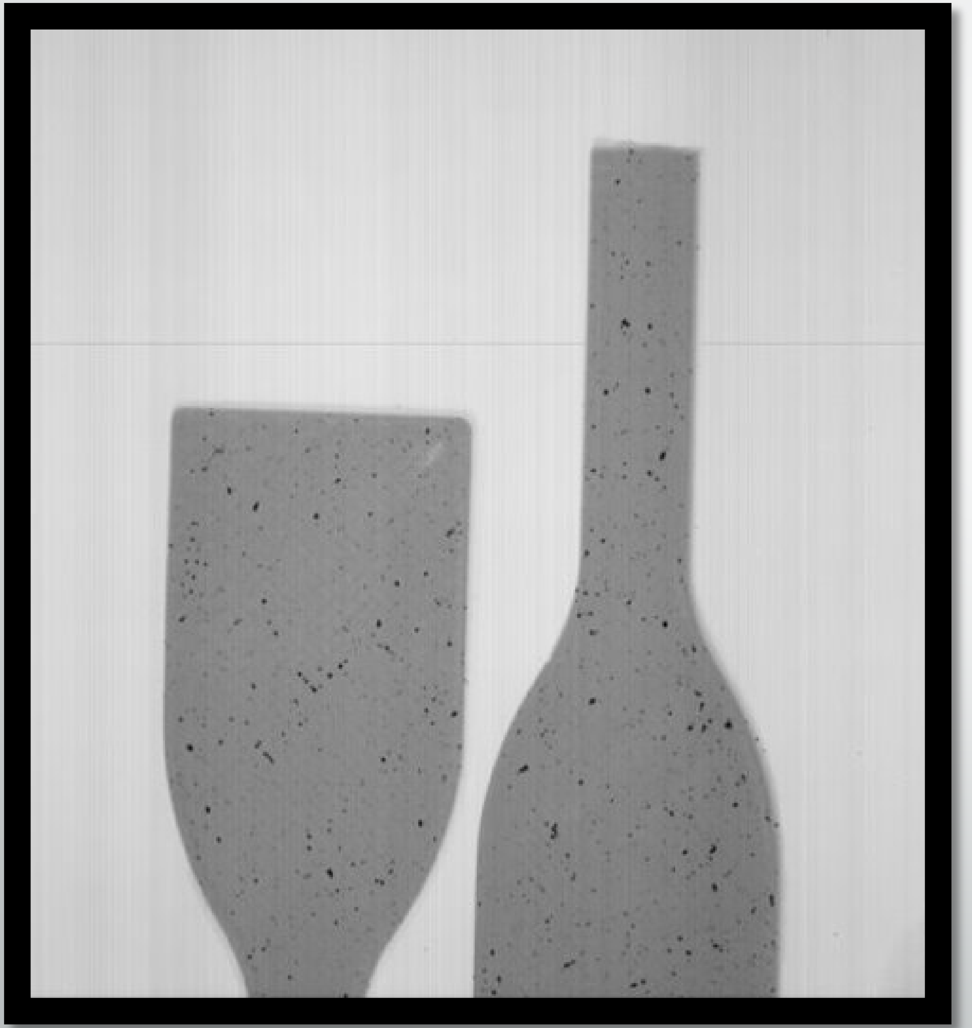


25wt_x50



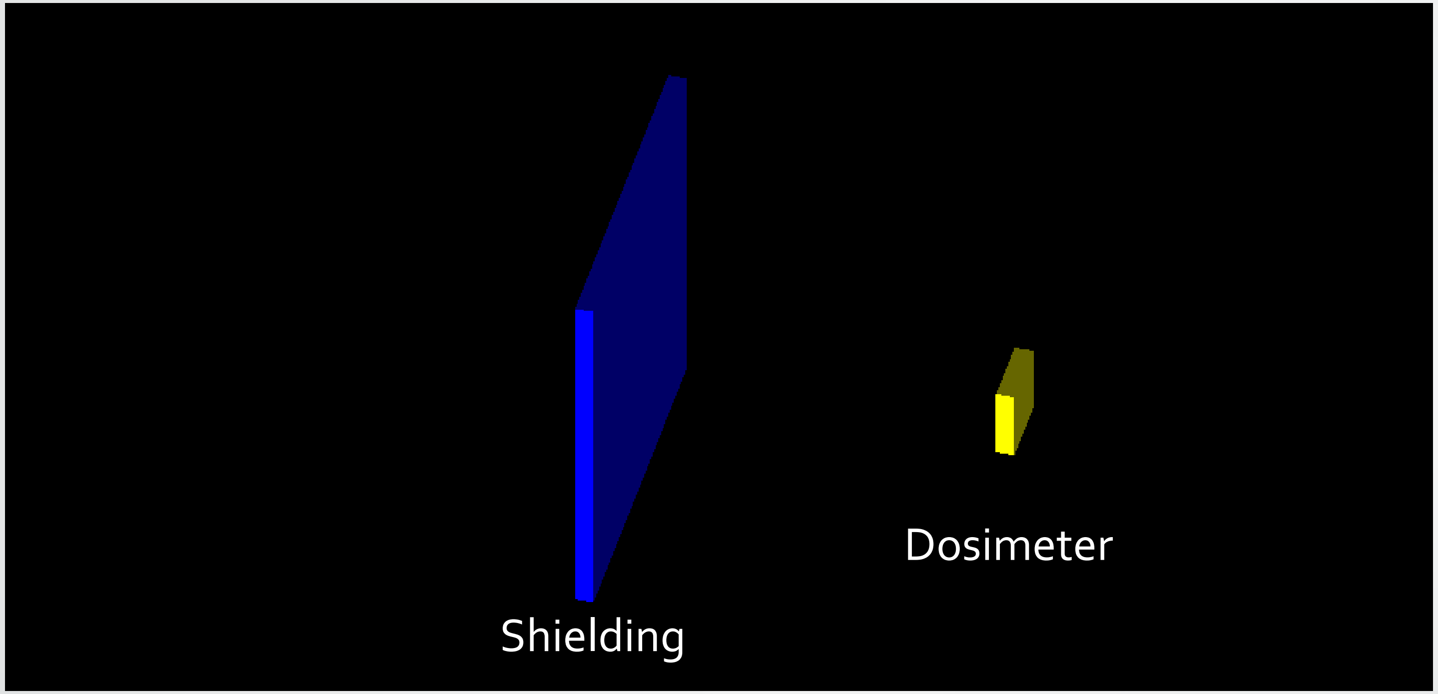
25wt_x100

X-Ray Testing



X-Ray results in January using ball mill (10%wt.)

Left to right: 0% BF, 25% BF, 40% BF



GEANT4 Simulation

*Simulation was coded and compiled by Dr. Robert McTaggart. Special thanks to him and his efforts for running the simulation.

Simulation Set-Up

Design*

- Approximately 100,000 gamma rays "fired" at shield in one-dimensional beam with varied distance
- Dosimeter
  - Calcium Fluoride, CaF_2
- Shield composition
  - 75% ABS
  - 25% BF
- Shield dimensions
  - 0.5 x 10 x 10 cm

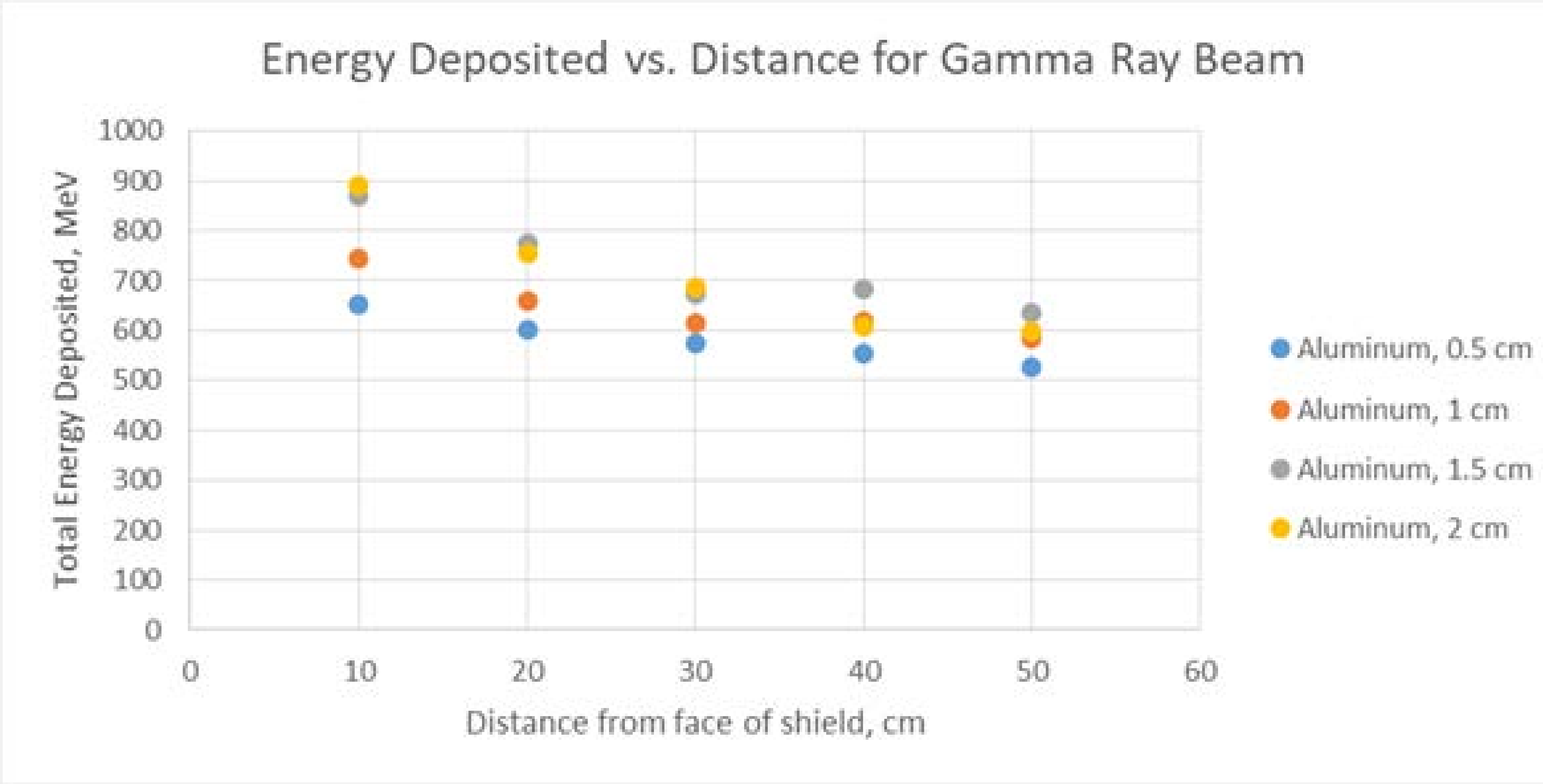
Chemical Breakdown

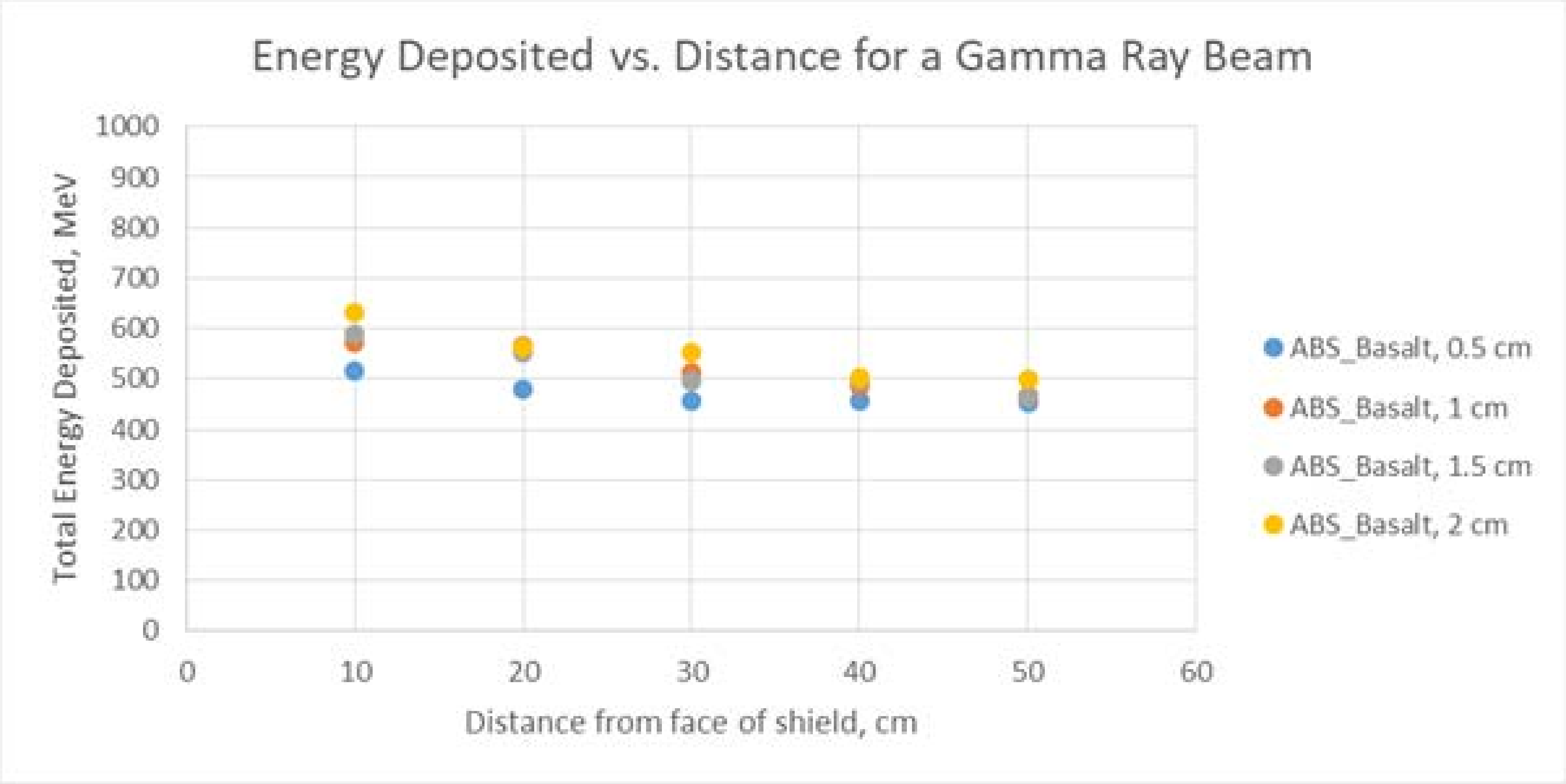
- Typical Composition of a Basalt sample:
  - SiO_2 @ ~50%wt.
  - Al_2O_3 @ ~14%wt.
  - MgO @ ~12%wt.
  - CaO @ ~10%wt.
  - TiO_2 @ ~0.5-2%wt.
  - FeO @ ~12%wt.
- ABS Composition
  - $(C_8H_8)\cdot(C_4H_6)\cdot(C_3H_3N)$

Sources

Basalt: L. Harnois and R. Stevenson, "Major and trace elements geochemistry of basalts and trachyphonolites from Huahine Island, Society archipelago (French Polynesia)," Bull. Soc. Geol, pp. 179–186, 2006

ABS: Acrylonitrile Butadiene Styrene: Detailed Information About ABS and its Features," *Density of Plastics Material: Technical Properties Table*. [Online]. Available: https://omnexus.specialchem.com/selection-guide/acrylonitrile-butadiene-styrene-abs-plastic


Energy Deposited vs. Distance for Gamma Ray Beam
Total Energy Deposited, MeV
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
Distance from face of shield, cm
Aluminum, 0.5 cm
Aluminum, 1 cm
Aluminum, 1.5 cm
Aluminum, 2 cm



Energy Deposited vs. Distance for a Gamma Ray Beam
Total Energy Deposited, MeV
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
Distance from face of shield, cm
ABS_Basalt, 0.5 cm
ABS_Basalt, 1 cm
ABS_Basalt, 1.5 cm
ABS_Basalt, 2 cm

Fiber Analysis Updates

Actual Percent Weight of Filaments

- Thorough Analysis
  - Repetition of experiment
- Originally began with 25%wt
  - 12mm sample had 10.27%
  - 3mm sample had 22.48%
- Originally began with 40%wt
  - 3mm sample had 35.75%

Post-Separation of 12mm fibers from ABS/Acetone solution

Post-Separation of 3mm fibers from ABS/Acetone solution

System Updates and Current Work

New Fan Cooler

- Guides filament with proper airflow
- Allows complete hardening of filament before entering puller
- Contains variable speed fans to set air flow at desired rate.
- Features a digital voltmeter and ammeter.

Loss-In-Weight Feeder

- ABS and basalt fibers will be loaded into separate funnels.
- Two separate motors (one for ABS and the other for basalt fibers) will spin a screw conveyor at the desired weight ratio to allow consistent mixing.
- Will also eliminate fibers nesting at bottom of funnel which prevents proper mixing.
- Will save time from no longer hand feeding the extruder and eliminate human error by spilling any material when hand feeding the extruder.

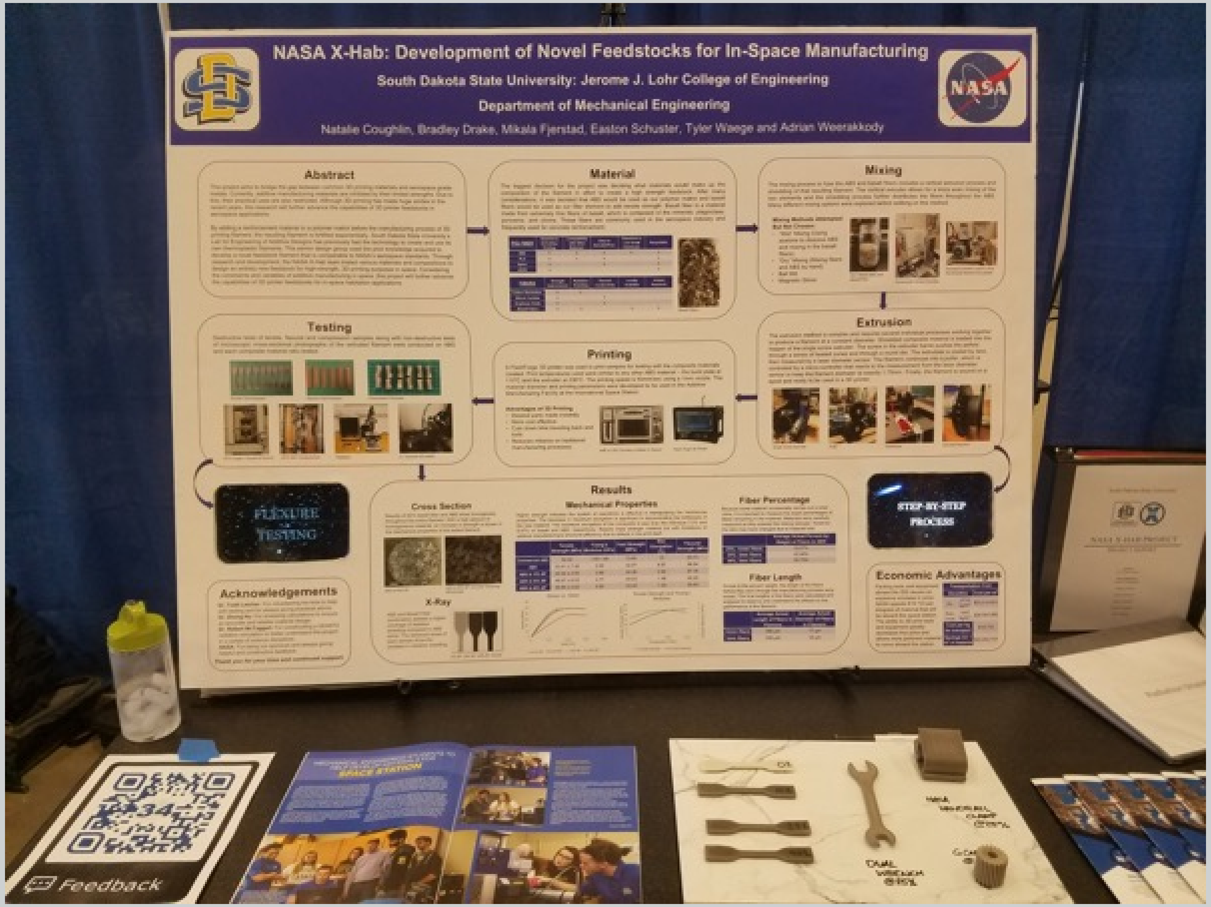
Economic Worth

- Costs $19,733 per kg to transport material to space
- Costs less to transport $1m^3$ of ABS with 25% basalt fiber than $1m^3$ of aluminum to space.

ENGINEERING EXPO

SOUTH DAKOTA STATE UNIVERSITY

2nd place out of design teams across all engineering, computer science , and agricultural disciplines


NASA X-Hab: Development of Novel Feedstocks for In-Space Manufacturing
South Dakota State University: Jerome J. Lohr College of Engineering
Department of Mechanical Engineering
Natalie Coughlin, Bradley Drake, Mikala Fjerstad, Easton Schuster, Tyler Waege and Adrian Weerakkody
NASA
Abstract
Material
Mixing
Testing
Printing
Extrusion
Results
Cross Section
Mechanical Properties
Fiber Percentage
Fiber Length
X-Ray
Acknowledgements
Economic Advantages
FLEXURE TESTING
STEP-BY-STEP PROCESS
Feedback


Economic Advantages
NASA X-HAB PROJECT
CREATOR PRO

NASA X-Hab: Development of Novel Feedstocks for In-Space Manufacturing

South Dakota State University: Jerome J. Lohr College of Engineering

Department of Mechanical Engineering

Natalie Coughlin, Bradley Drake, Mikala Fjerstad, Easton Schuster, Tyler Waege and Adrian Weerakkody

Abstract

This project aims to bridge the gap between common 3D printing materials and aerospace grade metals. Currently, additive manufacturing materials are inhibited by their limited strengths. Due to this, their practical uses are also restricted. Although 3D printing has made huge strides in the recent years, this research will further advance the capabilities of 3D printer feedstocks in aerospace applications.

By adding a reinforcement material to a polymer matrix before the manufacturing process of 3D printing filament, the resulting filament is fortified exponentially. South Dakota State University's Lab for Engineering of Additive Designs: Education and Research has previously had the technology to create and use its own thermoplastic filaments. This senior design group used the prior knowledge acquired to develop a novel feedstock filament that is comparable to NASA's aerospace standards. Through research and development, the NASA X-Hab team trialed various materials and compositions in order to design an entirely new feedstock for high-strength, 3D printing purposes in space. Considering the constraints and variables of additive manufacturing in space, this project will strive for the strength requirements set by NASA.

Material

The biggest decision for the project was deciding what materials would make up the composition of the filament in effort to create a high strength feedstock. After many considerations, it was decided that ABS would be used as our polymer matrix and basalt fibers would be used as our filler element to add tensile strength. Basalt fiber is a material made from extremely fine fibers of basalt, which is composed of the minerals: plagioclase, pyroxene, and olivine. These fibers are commonly used in the aerospace industry and frequently used for concrete reinforcement.

POLYMER	Experience Extruding / Printing	Compatibility with Other Materials	Easy to Extrude/Print	Dissolves in Low Grade Chemicals	Recyclable
ABS	X	X	X	X	X
PLA	X	X	X		X
Nylon	X		X		X
HDPE	X				X

FIBERS	Strength Improvement	Radiation Shielding	Thermal Conductivity	Locally Available	Unique Research
Carbon Nanotubes	X	X			
Silicon Carbide	X		X		
Graphene Oxide	X		X		
Basalt Fibers	X	X		X	X


Basalt Fibers

Mixing

The mixing process to fuse the ABS and basalt fibers includes a vertical extrusion process and shredding of that resulting filament. The vertical extruder allows for a more even mixing of the two elements and the shredding process further distributes the fibers throughout the ABS. Many different mixing options were explored before settling on this method.

Mixing Methods Attempted But Not Chosen:
- "Wet" Mixing (Using acetone to dissolve ABS and mixing in the basalt fibers)
- "Dry" Mixing (Mixing fibers and ABS by hand)
- Ball Mill
- Magnetic Stirrer


"Dry" Mixed ABS and Basalt Fiber

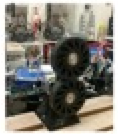

Randcastle Vertical Extruder

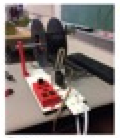

Industrial shredder used to chop Randcastle filament into pellets

Extrusion

The extrusion method is complex and requires several individual processes working together to produce a filament at a constant diameter. Shredded composite material is loaded into the hopper of the single screw extruder. The screw in the extruder barrel pushes the pellets through a series of heated zones and through a round die. The extrudate is cooled by fans, then measured by a laser diameter sensor. The filament continues into a puller, which is controlled by a micro-controller that reacts to the measurement from the laser diameter sensor to keep the filament diameter at exactly 1.75mm. Finally, the filament is wound on a spool and ready to be used in a 3D printer.


Single Screw Extruder


Puller

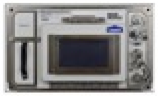

FilaWinder


Spooled Filament

Printing

A FlashForge 3D printer was used to print samples for testing with the composite materials created. Print temperatures used were similar to any other ABS material – the build plate at 110°C and the extruder at 230°C. The printing speed is 60mm/sec using a 1mm nozzle. The material diameter and printing parameters were developed to be used in the Additive Manufacturing Facility at the International Space Station.

Advantages of 3D Printing
- Desired parts made instantly
- More cost effective
- Cuts down time traveling back and forth
- Reduces reliance on traditional manufacturing processes

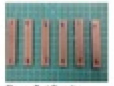

AMF on ISS (Courtesy of Made In Space)

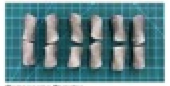

Flash Forge 3D Printer

Testing

Destructive tests of tensile, flexural and compression samples along with non-destructive tests of microscopic cross-sectional photographs of the extruded filament were conducted on ABS and each composite material ratio tested.


Tensile Test Samples


Flexure Test Samples


Compression Samples


MTS Insight: Tensile & Flexure


MTS 858: Compression

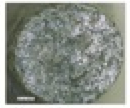

Keyence


CT Scanner NSI M500

Results

Cross Section

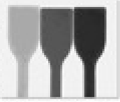
Initial result of 40% basalt fiber and ABS show homogeneity throughout the entire filament. Final result of the 40% basalt fiber and ABS exhibited an increase of homogenous material thus an increase in strength shown in mechanical properties.


ABS & 40% BF


ABS & 40% BF via Laser Scanning Microscope

X-Ray

ABS and Basalt Fiber combination exhibits a higher coverage of radiation shielding compared to ABS alone. The darkened areas of each sample show the increase in radiation shielding.


0% BF, 20% BF, 40% BF Tensile

Mechanical Properties

Higher strength indicates the system of operations is effective in manipulating the mechanical properties. The decrease in maximum elongation is significant in demonstrating the brittleness of the new material. The maximum elongation of the composite is less than the individual 3.2% and 9.97% of basalt and ABS, respectively. Results imply stronger material but with limitations of additive manufacturing's structural efficiency due to defects in the print itself.

	Tensile Strength (MPa)	Young's Modulus (GPa)	Yield Strength (MPa)	Max Elongation (%)	Flexural Strength (MPa)
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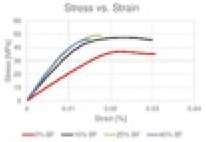
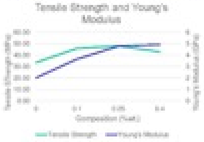




Fiber Percentage

Because some material occasionally comes out a relief valve, it is important to measure the exact percentages of fibers remaining in the material. Materials were carefully measured as they entered the mixing extruder. However, the ratio may have changed due to material loss.

	Average Actual Percent by Weight of Fibers to ABS
25%, 12mm fibers	10.27%
25%, 3mm fibers	22.48%
40%, 3mm fibers	35.75%

Fiber Length

Similar to the percent weight, the length of the fibers before they went through the manufacturing process were known. The final lengths of the fibers were calculated and analyzed to observe and understand the effects on the performance of the filament.

	Average Actual Length of Fibers in Filament	Average Actual Diameter of Fibers in Filament
12mm fibers	386 μm	17 μm
3mm fibers	335 μm	16 μm

Acknowledgements

Dr. Todd Letcher- For volunteering his time to help with testing and for always giving practical advice.
Dr. Zhong Hu- For reviewing calculations to ensure an accurate and reliable material design.
Dr. Robert McTaggart- For constructing a GEANT4 radiation simulation to better understand this project in a variety of science disciplines.
NASA- For being our sponsors and always giving helpful and constructive feedback.

Thank you for your time and continued support.

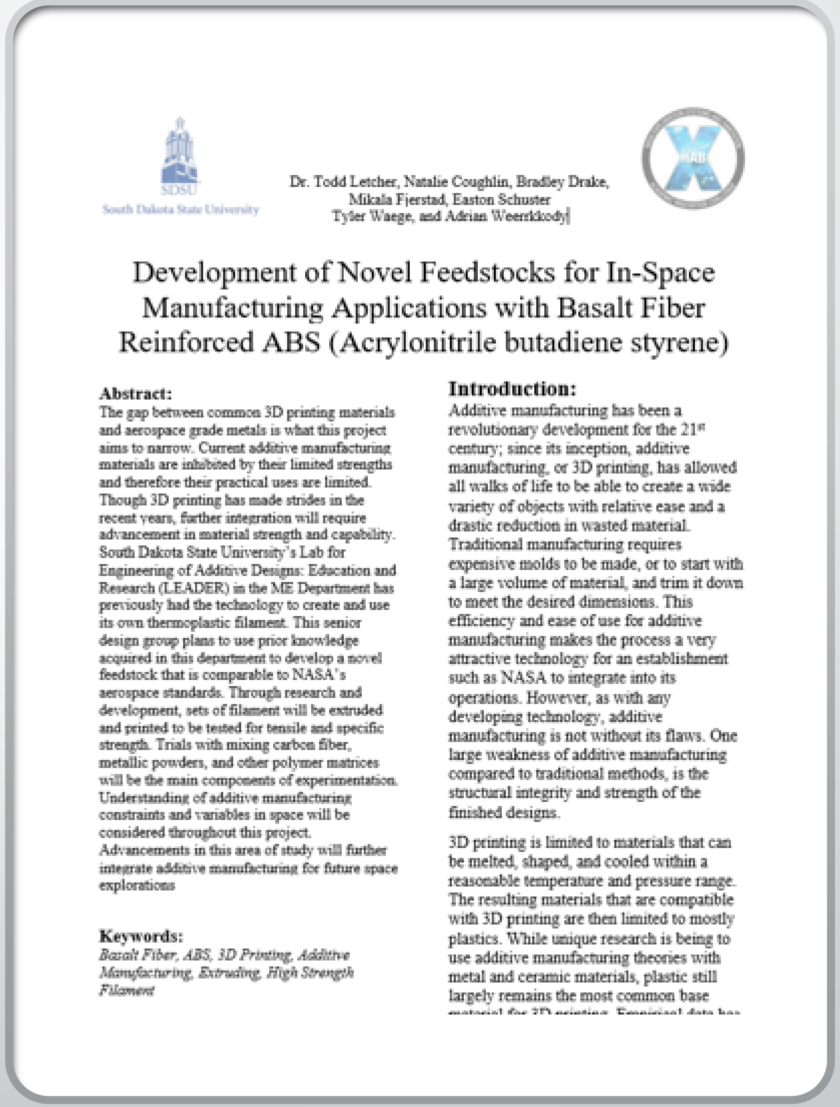
Economic Advantages

Packing tools and equipment aboard the ISS causes an explosive increase in price. NASA spends $19,733 per kilogram of material that will be aboard the space station. The ability to 3D print tools and equipment greatly decreases this price and allows more pertinent material to come aboard the station.

Transportation Cost		
Densities		Cost per m³
[illegible]	2712 kg/m³	$53,516,601
[illegible]	1447 kg/m³	$28,563,893
Cost per kg for transport		$19,733
Savings for 1 m³ of material		$24,952,707

Publication

- Currently beginning final testing for journal article
- Publications being considered:
  - Advances in Polymer Technology
  - Journal of Applied Polymer Science
  - Journal of Composites Science
  - Virtual and Physical Prototyping



SDSU
South Dakota State University

Dr. Todd Letcher, Natalie Coughlin, Bradley Drake, Mikala Fjerstad, Easton Schuster Tyler Waege, and Adrian Weerikkody

Development of Novel Feedstocks for In-Space Manufacturing Applications with Basalt Fiber Reinforced ABS (Acrylonitrile butadiene styrene)

Abstract:
The gap between common 3D printing materials and aerospace grade metals is what this project aims to narrow. Current additive manufacturing materials are inhibited by their limited strengths and therefore their practical uses are limited. Though 3D printing has made strides in the recent years, further integration will require advancement in material strength and capability. South Dakota State University's Lab for Engineering of Additive Designs: Education and Research (LEADER) in the ME Department has previously had the technology to create and use its own thermoplastic filament. This senior design group plans to use prior knowledge acquired in this department to develop a novel feedstock that is comparable to NASA's aerospace standards. Through research and development, sets of filament will be extruded and printed to be tested for tensile and specific strength. Trials with mixing carbon fiber, metallic powders, and other polymer matrices will be the main components of experimentation. Understanding of additive manufacturing constraints and variables in space will be considered throughout this project. Advancements in this area of study will further integrate additive manufacturing for future space explorations

Keywords:
Basalt Fiber, ABS, 3D Printing, Additive Manufacturing, Extruding, High Strength Filament

Introduction:
Additive manufacturing has been a revolutionary development for the 21st century; since its inception, additive manufacturing, or 3D printing, has allowed all walks of life to be able to create a wide variety of objects with relative ease and a drastic reduction in wasted material. Traditional manufacturing requires expensive molds to be made, or to start with a large volume of material, and trim it down to meet the desired dimensions. This efficiency and ease of use for additive manufacturing makes the process a very attractive technology for an establishment such as NASA to integrate into its operations. However, as with any developing technology, additive manufacturing is not without its flaws. One large weakness of additive manufacturing compared to traditional methods, is the structural integrity and strength of the finished designs.

3D printing is limited to materials that can be melted, shaped, and cooled within a reasonable temperature and pressure range. The resulting materials that are compatible with 3D printing are then limited to mostly plastics. While unique research is being to use additive manufacturing theories with metal and ceramic materials, plastic still largely remains the most common base

Expected Deliverables

- 1 kg spool of material
  - 25%BF ?? - Please let us know which version you want
- Full technical report
  - Final draft of published manuscript
  - Will send to Christopher Roberts for distribution at NASA before submitting to publisher
- Brochure from Engineering Expo

Questions?

Final Acknowledgments and Appreciation

Thank you for giving us the opportunity to work on this Xhab project. We have learned so much through this process and are excited to compile the work into a journal paper. We hope that South Dakota State University can collaborate with NASA again in the future in an effort to advance space exploration.

All the best,

SDSU NASA X-HAB TEAM

SOUTH DAKOTA STATE UNIVERSITY

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