ORNL/SPR-2019/1341
TCR-AM-RPRT-001

Binder Jet Additive Multi-Material Manufacturing for the Transformational Challenge Reactor

Christopher Shafer
Amy Elliott, Ph.D.
8/23/2019

OAK RIDGE NATIONAL LABORATORY
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U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
Energy and Transportation Science Division

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Date Published:

August 23, 2019

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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ACKNOWLEDGMENTS

The authors would like to acknowledge technical professionals from Oak Ridge National Laboratory: William Carter for his assistance with controls integration, and Kristin Zaloudek for her assistance with electrical system integration. The authors would also like to thank Scott Mersman and Nick Seagraff from the local vendor Modern Automation for their technical guidance and hardware supplying; Al Neal, Daniel Barrera, and Collin Hogan from Lenze for their controls hardware and software assistance; Juan Calderon and Mike Raymond for their assistance in selecting the correct print head for the research platform; and Ken Hillier, Simon Willis, and Charles Sharpe from Meteor for their guidance on using the 1201 Development Kit and navigating Meteor software.

ABSTRACT

Additive manufacturing (AM) is a process in which material is deposited in a layer-by-layer fashion, thereby building up a geometry. This contrasts with subtractive manufacturing in which material is removed from bulk feedstock to create a final geometry. Binder jet AM (BJAM) is a specific process in the AM field in which a binder, or glue, is selectively deposited on a bed of spread powder feedstock and cured. Binder is deposited with an inkjet printhead, which allows for high-resolution shaping of the powder layers. Compared with other AM processes, BJAM is fast, efficient, and scalable. Further, BJAM has one of the largest material selections of the powder AM processes as it can process ceramics, plastics, metals, and virtually any powdered material. Thus, the opportunity exists to leverage the versatility and productivity of BJAM to enable multi-material printing, the next generation of AM technology. The aim of this research is the design and manufacture of a purpose-built BJAM machine that can process multiple materials in its normal operation. This binder jet additive multi-material manufacturing ($BJAM^3$) machine will be able to produce parts that have multiple materials intra- and inter-layer. An example of this would be encapsulating metal spheres inside of a ceramic cube or vice versa. This $BJAM^3$ process adds another step of freedom to designing and manufacturing complex parts. The milestone for this work is to provide details on the technical progress made to date on the development of multi-material binder jetting and to facilitate simultaneous additive manufacturing of at least two different powder feedstocks.

1. PROCESS OVERVIEW

The binder jet additive manufacturing (BJAM) process flow begins with spreading a smooth layer of powder feedstock and then a binder is deposited in the 2D shape of a slice from the geometry, which is then partially cured by a heater. The deposit, spread, bind, and cure steps repeat until the geometry has been fabricated in the surrounding powder bed. The powder bed volume, with the internal bound geometry, is then placed in a low-temperature oven to fully cure the binder. After fully curing, the bound part can be handled by brushing away the unbound powder, which can be reused. At this stage, the bound and cured geometry is considered a green part and is strong enough to be handled. Next, the green part can be placed in a furnace to sinter to full density or sinter and infiltrate with a secondary material. In both cases, the binder burns off at a temperature below the material melting temperature until reaching the desired sintering temperature. Upon furnace cool down, the fused part can be processed further, such as with machining or polishing, or utilized in its current state.

The BJAM multi-material ($BJAM^3$) process flow is the same for fully curing, handling, and heat processing, but there are some changes in the powder spreading and binder stages before those take place. Since there are at least two materials being used, there must be an added step of removing the first unbound material, dispensing and spreading the second powder, and binding the second material selectively. An example of the layer cycle is shown in Figure 1.

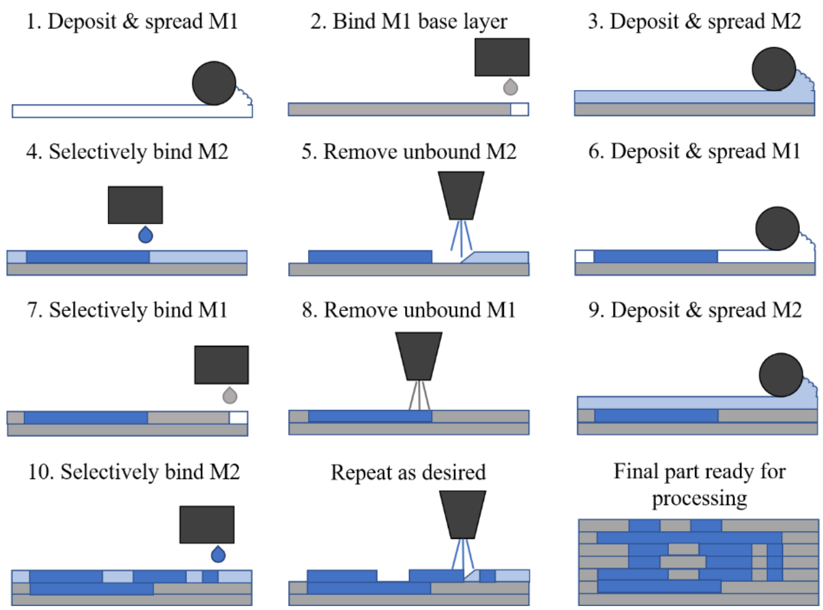


Figure 1. The BJAM³ layer process side view cross section of printing a part. Each layer has five steps: spread material 1 (M1), selectively bind and cure, remove M1 unbound powder, spread material 2 (M2), and selectively bind and cure.

As shown in Figure 1, the first layer after the base layer involves depositing one material and binding a secondary material around what will be the desired part geometry. This requires that a negative image of the slice of the part at that height be sent to the print head for printing and in the same layer, the positive version of that slice be sent to bind the powder in the void of the previous step. A representation of the images that the print head would print is shown in Figure 2. This spreading, binding, and removing of one material and repeating for the next material is where the design freedom shines. Specific material combinations, such as copper surrounding tungsten, could be used for high thermal or electrical conductivity and shielding in one part. Other possibilities include creating parts with matching furnace supports that would reduce final part distortion, and hard facing materials on tooling mold geometries, such as Stellite on H13 tool steel.

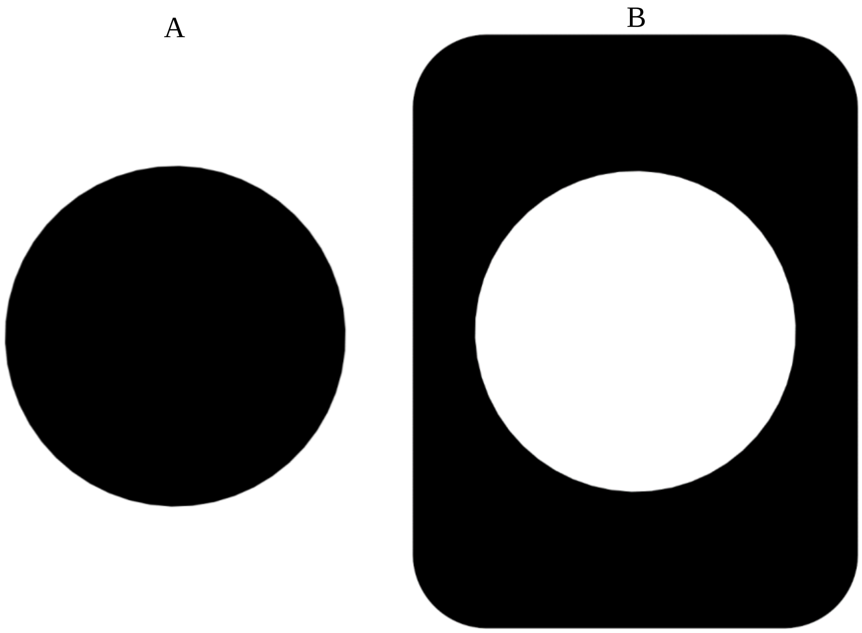


Figure 2. Top-down view of cylinder positive (A) and negative (B) images to be sent to the print head. The black regions are where the binder would be deposited.

The positive and negative images can both be printed with adjustable grayscale values to achieve the desired binder saturation percentage for each material. Some powder morphologies may absorb binder more readily than others, so the optimal saturations should be individually determined for each material. After completing the desired geometries with the desired materials, the standard BJAM steps may resume with the next step being to fully cure the build volume.

2. SYSTEM OVERVIEW

The major BJAM[3] machine subsystems include the platform and motion axes, powder handling components, inkjet system, controls, and safety systems. The platform on which all components are mounted is an optics table, which is shown in Figure 3A. The optics table provides a sturdy, corrosion-resistant, and precise platform with plenty of mounting holes for components.

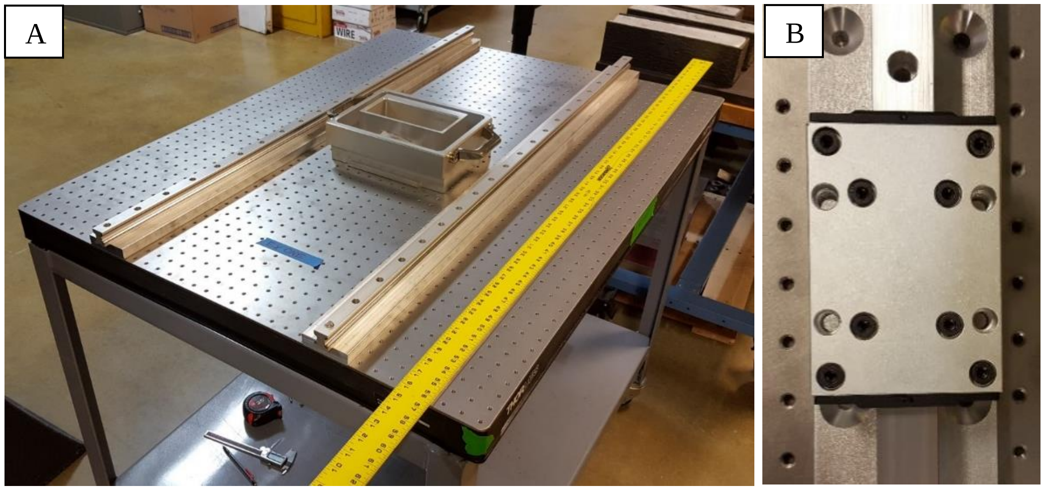


Figure 3. Early build stage image showing the optics table platform measuring 4’ × 3’ with linear rails (A) and carriage (B).

T-slot extrusions were utilized to allow for easy mounting of current and future hardware or sensors, modularity so that whole subassemblies could be removed as one unit, and wide availability for any design changes. The linear rails and matching roller carriages, with ball screws and servomotors driving loads, were chosen for their debris resistance and accuracy. The hoppers with cyclonic separators, roller, vacuum nozzles, and heater are on the powder handling axis, denoted at the X2 axis in Figure 4. The inkjet system includes the print head, capping station, wiping station with drain, peristaltic pumps for fluids, fluid reservoirs, and circuit boards on the X1 and Y axes. Controls were handled in conjunction between Lenze and Meteor hardware and software interfaces. Lenze was used for controlling axes motion with subsystem inputs and outputs while Meteor was used to control print head firing and image processing. Safety systems were monitored through Lenze hardware by an emergency stop button and enclosure door latches. Hard stops and ball screw shields were also put in place to protect hardware and operators.

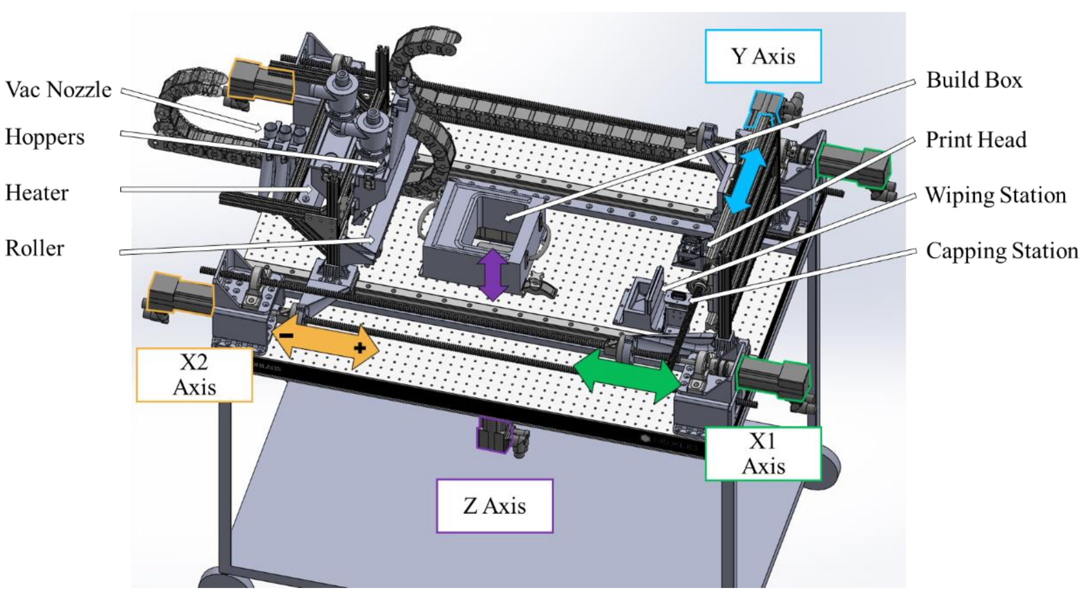


Figure 4. The component and axes setup and naming conventions used. Each axis can move in two directions as represented by arrows. The X1 and X2 axes are mounted on the same linear rail system, the Y axis is mounted onto the X1 axis, and the Z axis moves perpendicular to the plane of the platform.

2.1 LINEAR MOTION

Precision ball screws were chosen for axis motion for their reliability, accuracy, and strength. Typical setups with belts and cantilevered shafts were avoided as belts can stretch or slip and cantilevered shafts reduce bearing lifetime. All screws were supported on both ends with the ball screw nut, or load, between the supports, which is shown in Figure 5. Due to the relatively low load and velocity at which the axes would move, pillow bearings were used as end supports. The screw size was chosen to handle at least double the load of the heaviest powders that could potentially be used, such as if both hoppers were filled with tungsten, which is nearly double the density of lead. The ball screws, nuts, and bearings were of a standard size for simple replacement ordering, if needed. The screws would be protected from powder debris by shielding, which would also protect operators.

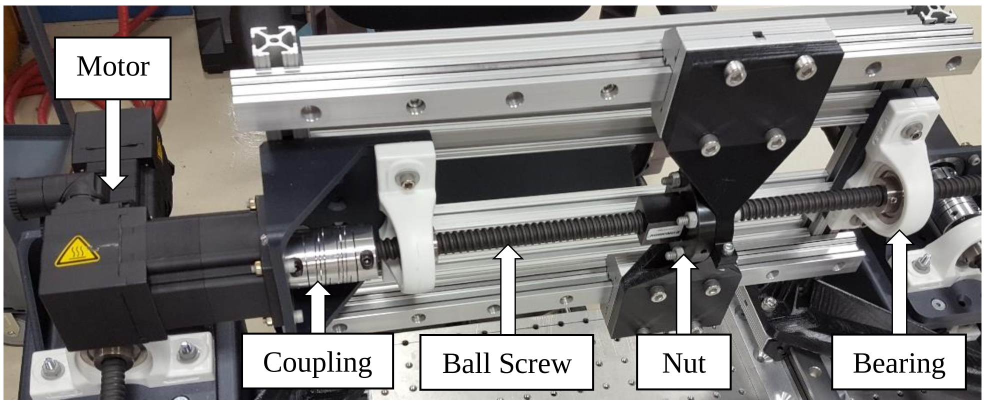


Figure 5. Servomotor-driven ball screw with ultra corrosion-resistant pillow bearing end supports and nut between supports.

2.2 ACTUATORS

Servomotors were chosen for their accuracy and power; two motors were used for each major axis to reduce uneven forces and decrease the average load that each motor would generate, thereby increasing their lifetime. The motors were selected to handle at least double the heaviest possible loading of powder. The Z axis motor was the same type as the other five motors, but with an added motor brake. The brake would prevent the Z axis from moving if motor or machine power is cut off; this way, a build would not fail by the Z axis losing its position. A flexible coupler was used between each of the ball screws and servomotors to account for slight misalignments and to protect the motors from damage as the coupler should be the first point of failure.

2.3 POWDER STORAGE AND DISPENSING

The powder handling axis, X2, consists of the hoppers with cyclonic separators, roller, vacuum nozzles, and heater. Each individual hopper contains, dispenses, and collects powder material. The hopper design, shown in Figure 6B, has one vertical wall and one 45° wall. The vertical wall allowed for easy mounting and no surface for powder to compact on without flowing. It is possible for powders to compact so much that they can bridge gaps and not fall out of openings, or that just the central column of powder would flow while the sides do not move. To prevent this, the 45° wall was designed to allow for a larger powder volume and a good location for an agitator to shake the wall to promote powder mixing and flow. Not all powder would freely flow from the hopper and the only place that it could collect and compact would be on the angled wall. The side walls were kept straight to eliminate additional compaction areas.

The hopper exit opening was created to be wider than required for standard sized powders because some powders, such as sand, can have much larger particle diameters on average. The powder would drop onto the dispensing plate when exiting the hopper and must overcome a 90° turn to fall onto the powder bed. This 90° turn and lip on the dispensing plate would prevent powder from exiting when not desired, such as when the axis is in motion. The dispensing plate was designed to be adjustable if different powders needed a greater distance between the plate and hopper exit. A motor with an offset shaft was used to create the vibrations in the angled wall, which would encourage powder motion. The motor rotation speed could be altered as some powders would need more vibrations to flow well. The motor was fixed to the 45° wall on the outside by two supports to evenly support the offset shaft and also provide two points of contact to agitate the powder. The hopper lid was designed to be easily removable yet create a seal to prevent powder lofting into the air when unwanted. A port for powder refilling and a port for powder recollection via a cyclone separator were both designed into the hopper lid. Two individual hoppers were created to fulfill the multi-material design process goal where two powder feedstocks could be printed in the same build and layer. The prototype material used was Ultem 9085, chosen for its strength, abrasion resistance, and chemical resistance, along with its availability at the Manufacturing Demonstration Facility.

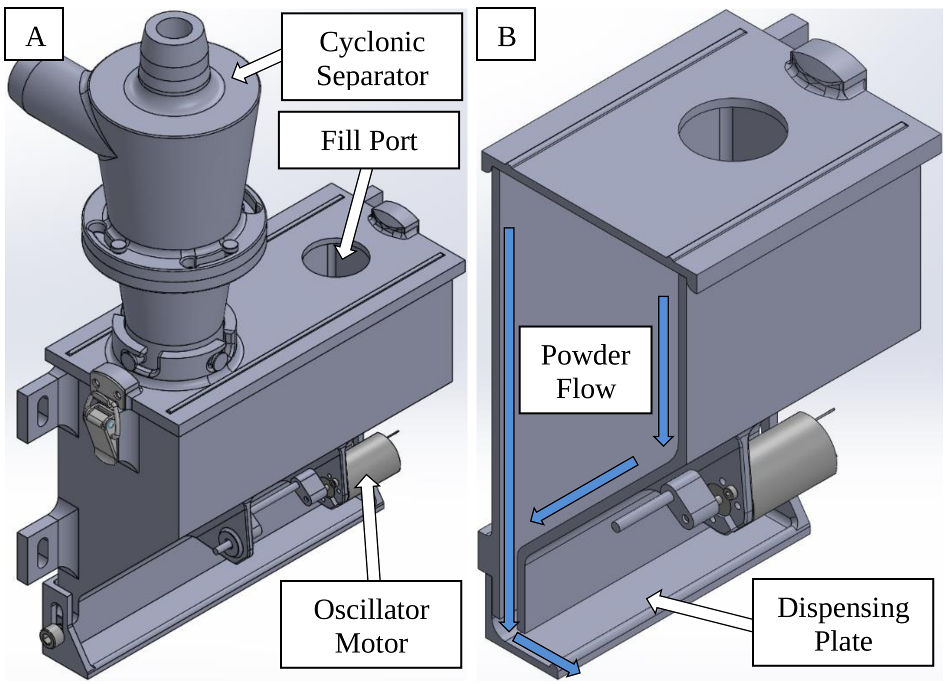


Figure 6. Hopper with cyclonic separator and oscillator motor (A); hopper cutaway showing the dispensing plate and powder flow represented by blue arrows (B).

2.4 POWDER RECOLLECTION

The cyclonic powder separator, shown in Figure 6, would allow the selected powder to return to its hopper without an operator being required to remove or transfer powder manually. The cyclone is created by suction at the top and the material is drawn in through the tube that is tangent to the curve of the cone, which would have a nozzle close to the print bed to pick up powder. The velocity of the cyclone forces the powder to drop out of the vortex and into the hopper while the remaining air can continue through the top to the static dissipative HEPA vacuum. The external design is such that the top and bottom half of the component could twist lock or separate for easy replacement. There are two vacuum nozzles that return material from the print bed to the corresponding hopper, shown by the arrows in Figure 7B.

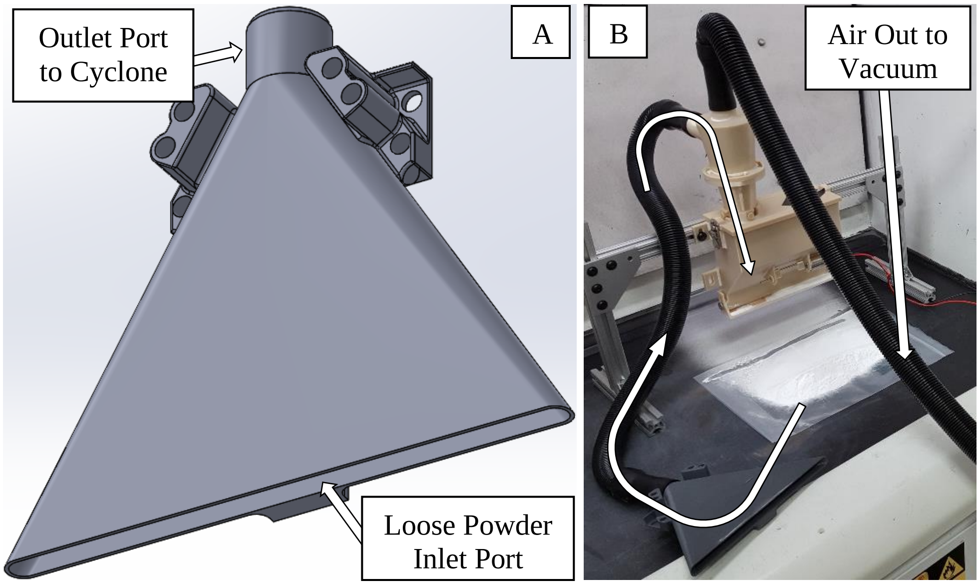


Figure 7. Vacuum nozzle (A), which passes closely over the print bed to pick up unbound powder and return it to the respective material's hopper through a cyclonic separator (B).

2.5 POWDER SPREADING

The roller assembly used to spread smooth layers of powder was a counter-rotating rod at a set distance above the top plane of the build box, with a motor attached at one end as shown in Figure 8. The rod was supported in two locations by corrosion- and dust-resistant bearings, similar to the ball screw supports for motion. This rod would smooth out freshly dispensed powders and would have a roller brush to clean it at the home position to reduce powder mixing from material stuck on its surface.

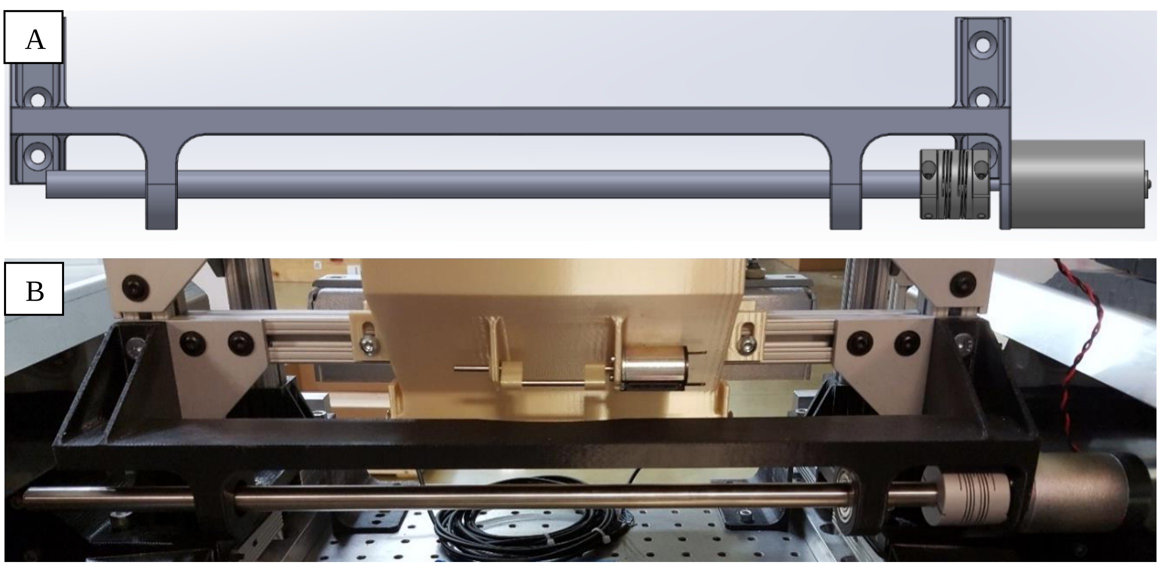


Figure 8. The counter-rotating roller assembly CAD model (A) and actual parts (B) used for spreading powders.

2.6 LAYER CURING

The infrared (IR) heater shown in Figure 9 is required for most binders; it would be used to evaporate the carrier fluid, leaving behind the polymer and partially curing the binder during printing. In order to vary the heater output, a silicon controlled rectifier (SCR) was required per the manufacturer's (Heraeus) instruction. SCR allows the input current to the heater to be controlled to ramp up and down, and also allows for a range of heater settings, 0–100%, for example. Different heater settings are often used as materials interact differently with the binder and may absorb more or less of it.

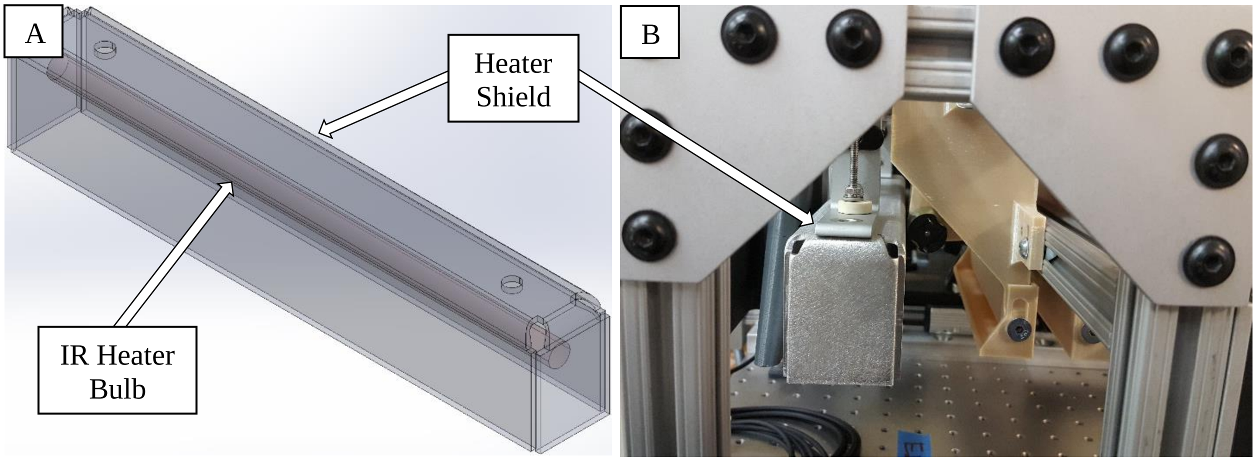


Figure 9. IR heater and sheet metal shielding CAD model (A) and actual part (B) that causes the IR energy to be directed downward onto the print bed to partially cure the binder.

2.7 INKJET SYSTEM

The print head, capping station, wiping station with drain, peristaltic pumps for fluids, fluid reservoirs, and circuit boards are all the components of the inkjet system. A XAAR print head was chosen for its wide industry use, multi-nozzle row ability, binder compatibility, and future expandability. The XAAR 1201 print head has four rows of nozzles that each have their own liquid feed line, which would typically be for four colors with ink, but can also be used with all four being fed binder. Another possibility is that multi-part binders could also be jetted, similar to epoxy mixing. This would contrast conventional two-part reaction printing as in most cases, one part is mixed in with the powder feedstock while the other is deposited onto it. XAAR print heads can also be set up with multiple print heads running together, so the system would be easily scalable to deposit more binder in a larger area or even deposit binder in two directions to normalize deposition accuracy. A Meteor Development Kit was available for developing traditional systems but was adapted to work with the industrial-grade servomotors and drives. Print head circuit boards were also part of the Development Kit and they control when the print head receives the signal to fire or call for more binder. The wiping and capping stations were both designed by following the recommendations in the XAAR manual. Peristaltic pumps shown in Figure 10D were used to move binder, cleaner, and drain fluids. The pumps, tubing, and associated reservoirs were chosen for their chemical resistance to accept a wide range of possible future binder and cleaner fluids.

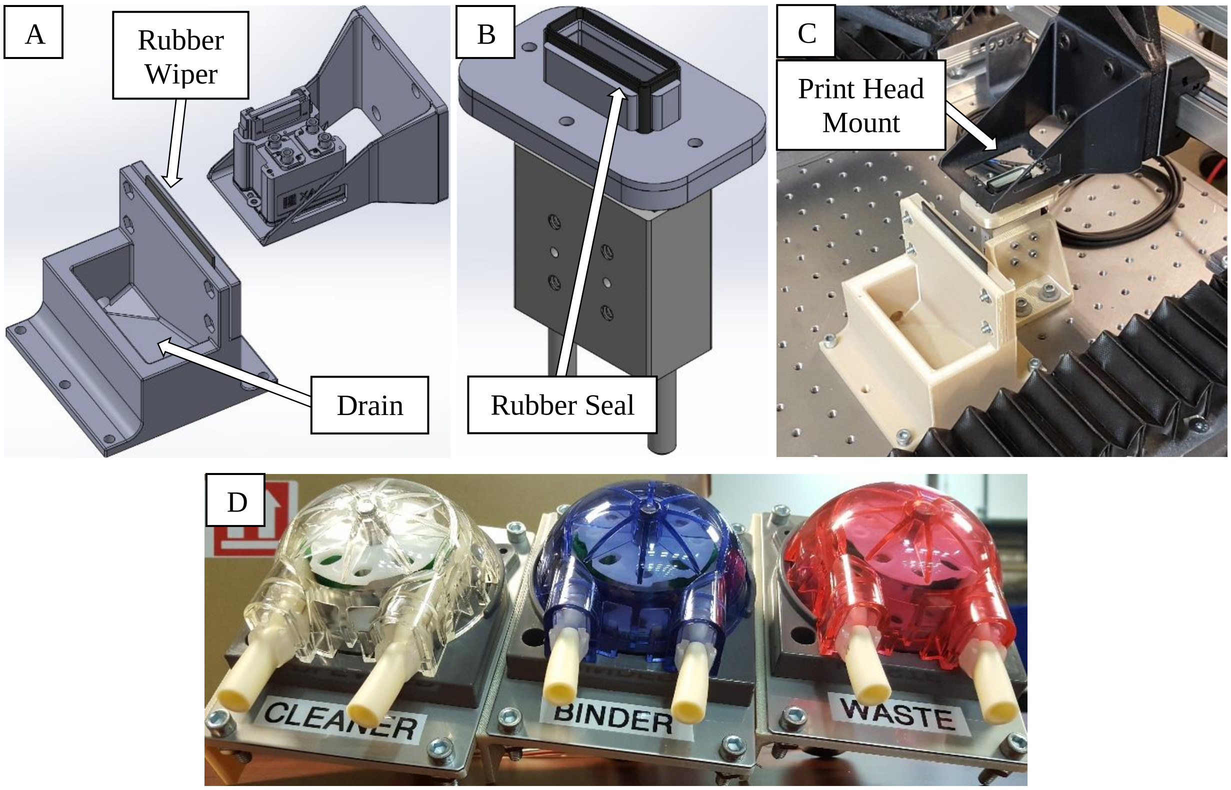


Figure 10. CAD model design of the wiping station with drain (A) and capping station with rubber seal to seal around print head nozzles (B); actual installation (C) and peristaltic pumps (D) for fluids that would connect to the print head and wiping station.

2.8 CONTROLS AND POWER

The system controls were handled by Lenze and Meteor hardware and software. The Lenze motion controller accepts a large variety of industrial control languages and has modularity to meet specific application needs. The controller was necessary as it could be expanded to manage all the input and output requirements and extra motors. The motion controller also sends signals to the servo drives in the drive enclosure shown in Figure 11. The BJAM^3 machine is powered by 480 V three phase wall power on a 30 A breaker in Hardin Valley Campus Building 2 with a transformer to step down the power for remaining system requirements.

Figure 11. The servomotor drive enclosure where servomotor power and position wires are connected to each motor. The motion controller sends signals to the drives for motion to begin.

An example layer cycle flowchart is shown in Figure 12. It can be expanded or scaled up with few to no modifications. The Meteor 1201 Development Kit came with necessary cards to control axes and the print head, but one of the cards did not have enough input and output for sensors and additional subassembly motors. The cards that were required to fire the print head had to be used in conjunction with the Lenze controller and drives. Print heads can be added to cover larger areas or fire in different directions, such as print heads that are offset by 90° from each other. A backup for a control system was LabView software and associated hardware to manually control component actions.

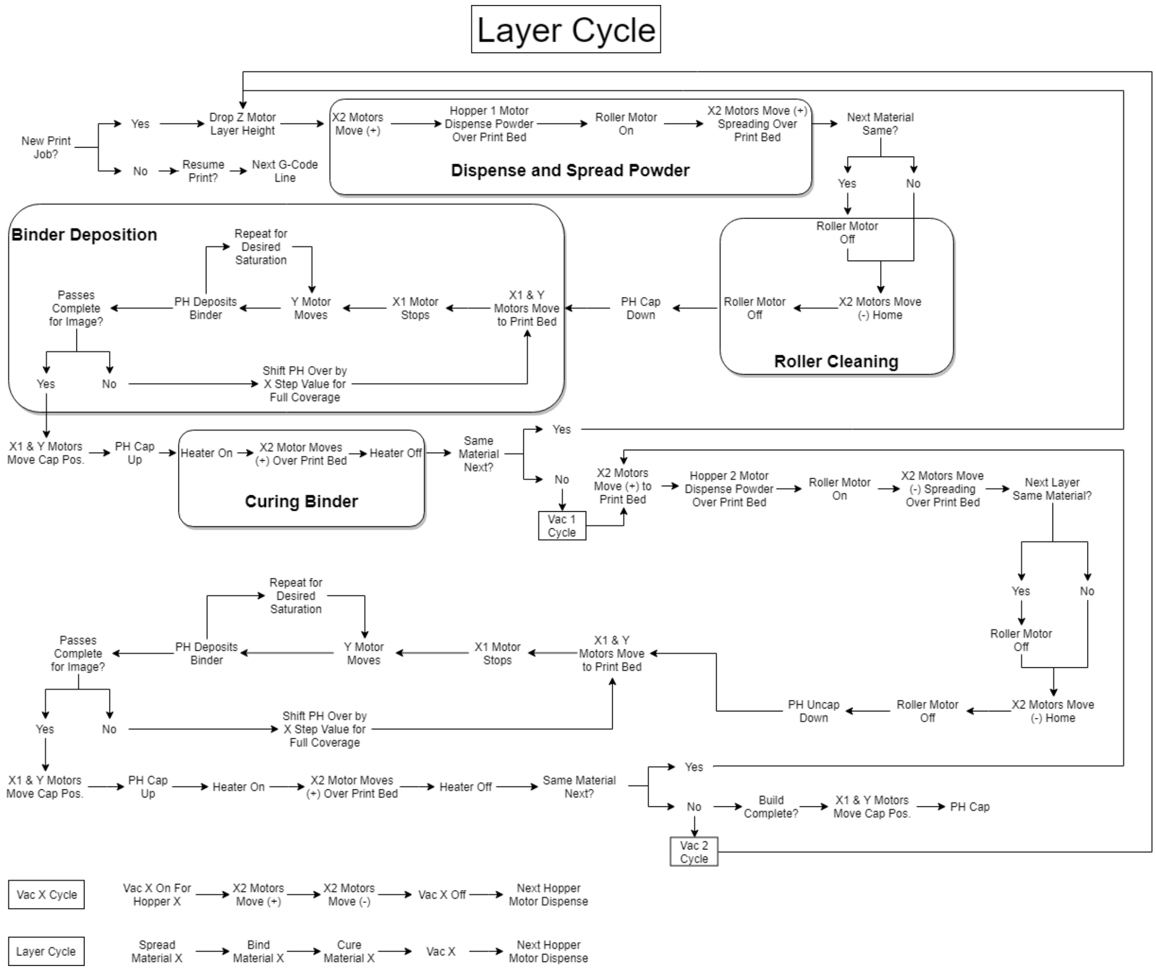


Figure 12. An example flowchart of a layer cycle that served as a guide as to whether Lenze or Meteor systems would need to control certain steps. Steps were developed with the goal of minimizing material mixing.

2.9 SAFETY

In addition to ball screw shields previously mentioned, other safety systems were in place to protect the machine and operators. The machine enclosure shown in Figure 13 was designed to prevent and contain powder contamination outside of the machine. This enclosure could also be sealed for use with inert gases if required, given that all the electronics could handle the environment or be relocated. There are doors for access to all areas of the printer, wide windows for viewing the processes, and the enclosure could be easily separated from the machine for transport or maintenance.

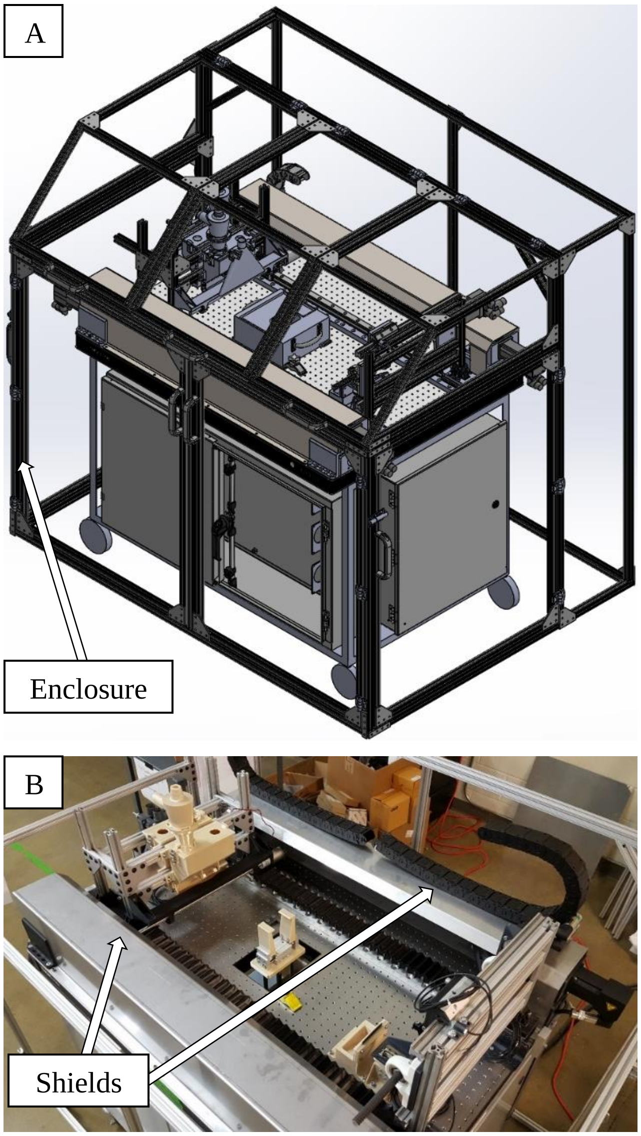


Figure 13. Machine enclosure (A) that would protect the surrounding environment from powder debris and shields (B) to protect the operator from axes and motors when in motion. Polycarbonate sheets would provide viewing windows and rubber seals would be in place for doors.

As in most cases with industrial machines, an emergency stop button was installed that could be pushed at the front of the machine to stop all motions in the event of an emergency. Another safety feature was that a third vacuum nozzle and vacuum were placed near the powder spreading roller on the X2 axis. In addition to the two material hopper vacuums, there was one vacuum and nozzle that was installed specifically to collect the lofted or airborne powder. This very fine powder can coat the inside of machines and interfere with proper performance of electronics and linear motion components, such as ball screws and rails. The dust-like materials would not be reused as they are far smaller than the majority in the powder distribution, often making them hazardous. The lofting vacuum was designed to travel with the powder dispensing axis in front of the roller and hoppers so that as powder is spread, any floating particles would be collected.

2.10 FINAL CONFIGURATION

The current configuration of the BJAM^3 machine is shown in Figure 14A, with enclosure access doors removed so that subsystem testing can be easily performed, and Figure 14B with the enclosure doors. Subsystems tested include hopper motors dispensing powder in a hood, roller motor rotation, vacuum recollection, and X1, X2, Y, and Z axis motion.

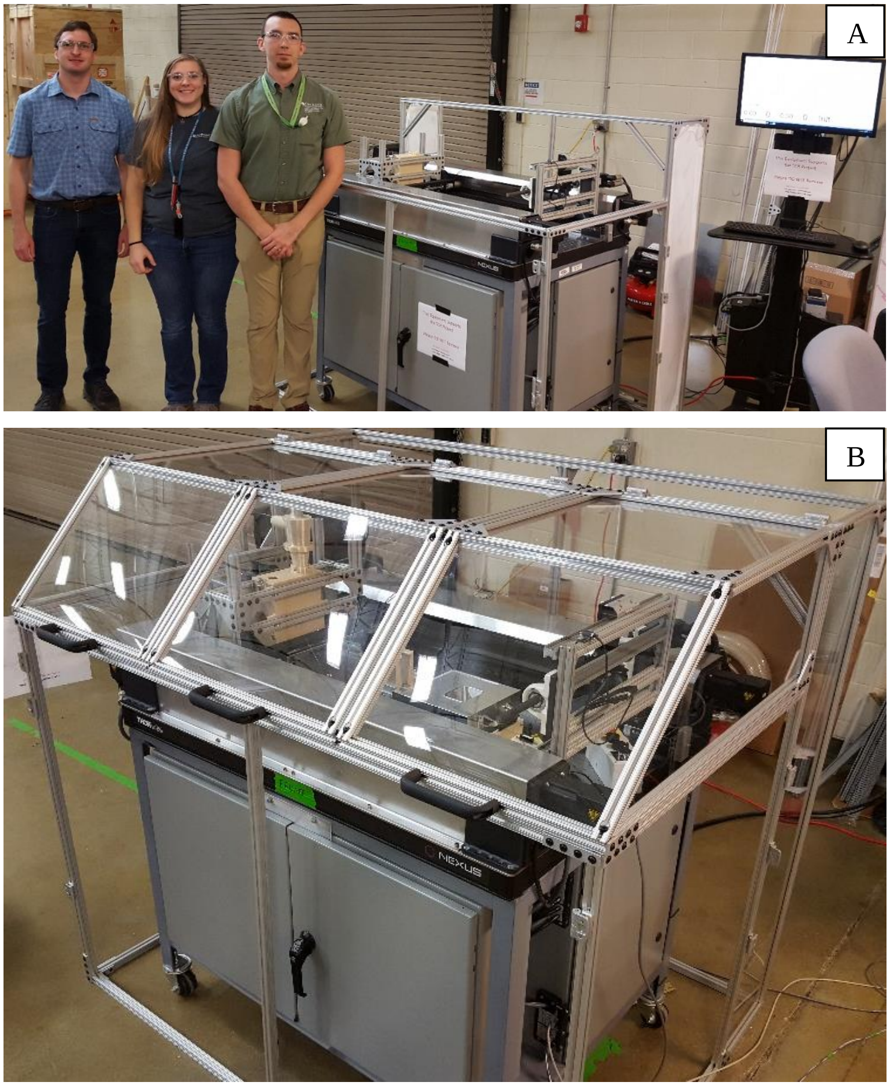


Figure 14. Design team (from left to right: William Carter, Kristin Zaloudek, and Chris Shafer) next to the BJAM^3 printer with machine and control enclosures next to the computer that will eventually have a singular user interface for process control (A) and machine enclosure with operator doors installed (B).

Currently, operators can load powder into hoppers, manually move and home axes, dispense powder from hoppers, smooth out dispensed powders with the roller, send images to the print head, and deliver fluids to the print head. The biggest challenge is the communication between the Lenze and Meteor components and software; multiple user interfaces are required for operation. Upon a final safety and electrical inspection, the machine can be used for developing settings and parts.

3. DESIGN PROGRESSION AND CHALLENGES

Initially, an open-source BJAM machine assembly called the "Plan B" was considered to achieve the multi-material goal. This printer had two separate powder feed volumes and one build volume with a size of 150 mm × 150mm × 100 mm in the middle as shown in Figure 15. This system was ruled out due to issues with powder mixing, the overall system not being easily cleanable, and the lack of room for additional systems. The accuracy and build volume of the desktop-scale printer were also concerns.

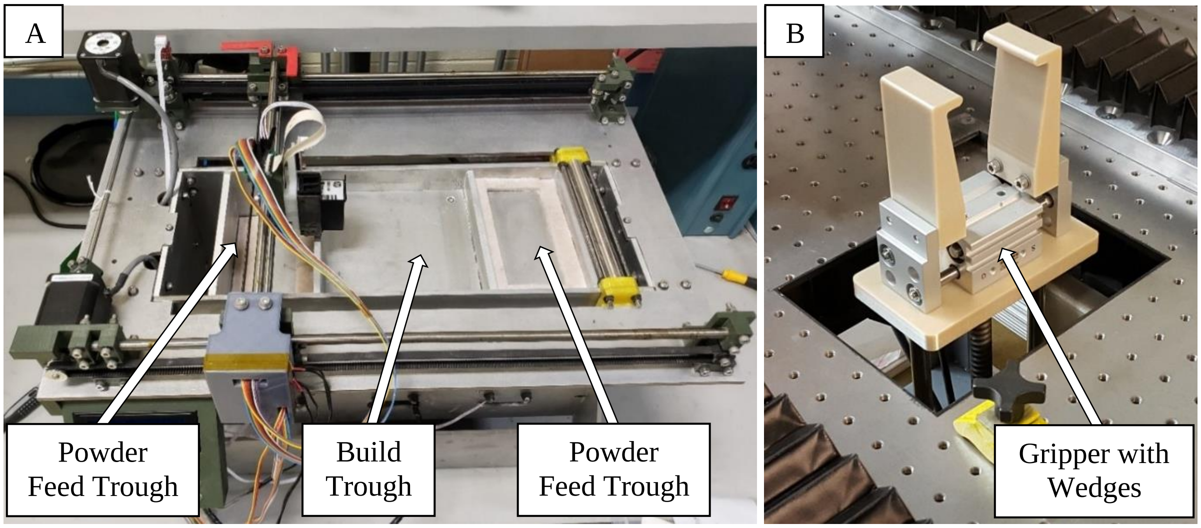


Figure 15. Plan B printer (A); BJAM[3] build plate pneumatic gripper with wedges (B) to grip the build plate.

One of the earliest design requirements for the BJAM[3] printer was to have a changeable build volume based on desired changes to make from the Plan B. Multiple build boxes can be used without complex changeover procedures on the BJAM[3] machine. The Z axis has a pneumatic parallel gripping mechanism that has two wedges that close to grab the bottom of the build plate. These wedges can be replaced or changed by the removal of two screws per wedge. All external build box dimensions were the same with the new design; only the 2D build area was varied. The small (30 mm × 40 mm × 100 mm), medium (60 mm × 80 mm × 100 mm), or large (120 mm × 160 mm × 100 mm) build box volume could be used depending on the material supply.

Early hopper designs for dispensing powder included a four-bar linkage to dispense scoops of powder from the dispensing plate. This mechanism dispensed too much powder, shown in Figure 16B, and also added to the number of moving parts that could fail when compared to the finalized design. The finalized dispensing mechanism involves vibrating one of the hopper walls to promote powder flow instead of moving the dispensing plate.

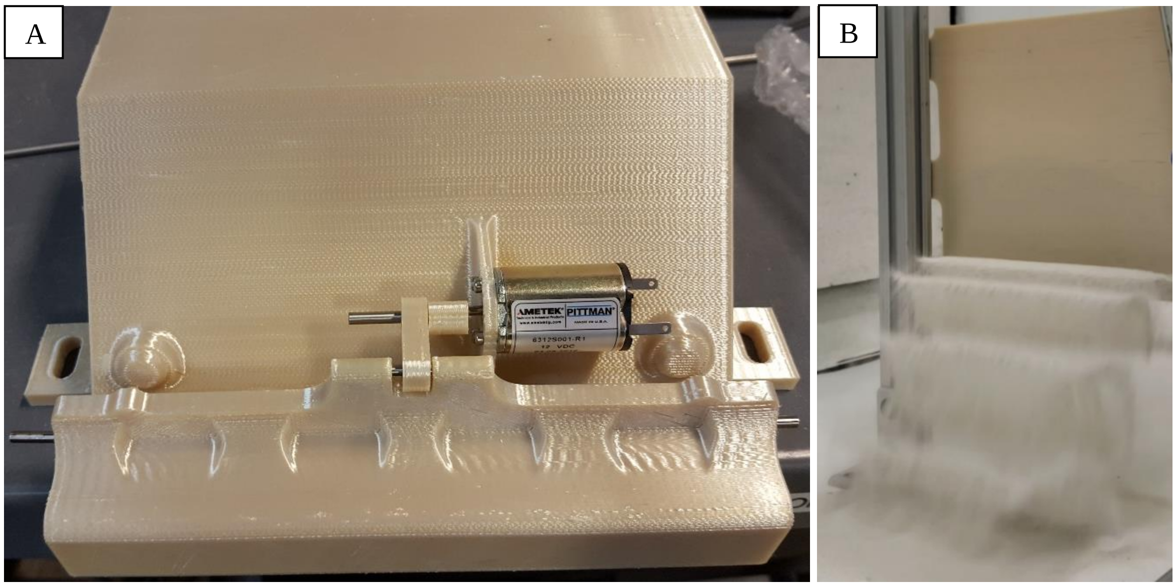


Figure 16. Early hopper four-bar mechanism design (A) that throws scoops of powder by rocking the dispensing plate back and forth; mechanism over-dispensing powder (B).

Another design change in the early stages of development was that individual vacuums and nozzles were used to return powder to the hoppers instead of one vacuum nozzle that was modular but had to be cleaned. Having individual vacuums and nozzles per hopper eliminated the need for a vacuum nozzle cleaning station. The original design intent behind the vacuum nozzle cleaning station, shown in Figure 17, was to remove any powder debris from nozzles when swapping powders.

Figure 17. Vacuum nozzle cleaning station sprayers and drain.

There were several challenges during the design and assembly of the BJAM^3 printer. The major challenge of this project has been determining which control components were required and could be used for current and future components. The communication ability between Lenze and Meteor cards software and hardware was also a challenge. Ideally, a single software interface can be implemented where parts and layers can be viewed, process parameters can be changed at any time during the build, and buttons can be used for manual control items, such as spreading again if needed. Due to potential difficulties, a back-up plan for controlling components utilizing LabView was put in place. Designs and components were made and chosen to be reliable so that the machine can be left unattended for long prints. Simple designs philosophies were used to ensure easy manufacturing of components and requiring little specialized knowledge as to their purpose. In general, the machine was created with expandability in mind: larger print beds, more print heads, and more hoppers for more material combinations could be achieved.

Designing for future expandability and multi-use components was a constant design objective so that the multi-material printer is adaptable for future changes. Communication between vendors was challenging at times, but after nondisclosure agreements were placed, a weekly meeting was set up with Lenze and Meteor to gain information and plan next steps with all parties present. There were some unexpected time lags between submitting a vendor quote and the order being placed by the ORNL purchasing department, by 10 days in the worst case with lead times on top of that. While this caused some minor delays, the project is still on track.

4. PRELIMINARY EVALUATION

Component and subsystem testing were conducted for each component as available. The early hopper and vacuum system were operated in an isolated environment, which ultimately led to a hopper redesign that reduced the number of parts in the oscillation motion and allowed for more controlled powder flow. The vacuum system was tested on the early hopper design, but initial results demonstrated that the hopper exit needed to be blocked by powder for proper operation of the cyclonic separator. Without powder blocking the hopper exit on the dispensing plate, air could flow in from the vacuum nozzle and hopper exit as shown in Figure 18, essentially creating two vacuum pathways. The lower section of the cyclonic separator, where the powder would exit, had to be restricted so that there was only one inlet for airflow from the vacuum nozzle and not the hopper powder exit.

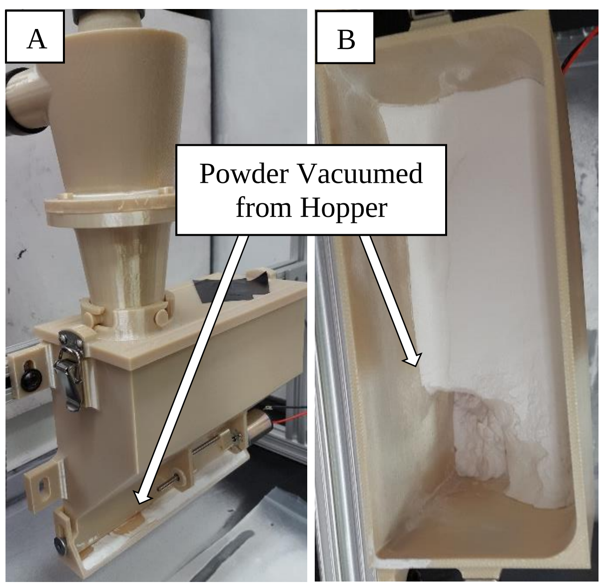


Figure 18. Unwanted recollection from hopper powder exit instead of vacuum nozzle (A) and top-down view without hopper lid (B).

To allow for only one inlet, a linear solenoid will be used to close the bottom of the hopper so that the cyclonic separator can operate properly with only two airflow pathways and collect powder. The difference in airflow between an open and closed hopper bottom is shown in Figure 19 with B showing that no particles exit to the vacuum through the top of the cyclonic separator.

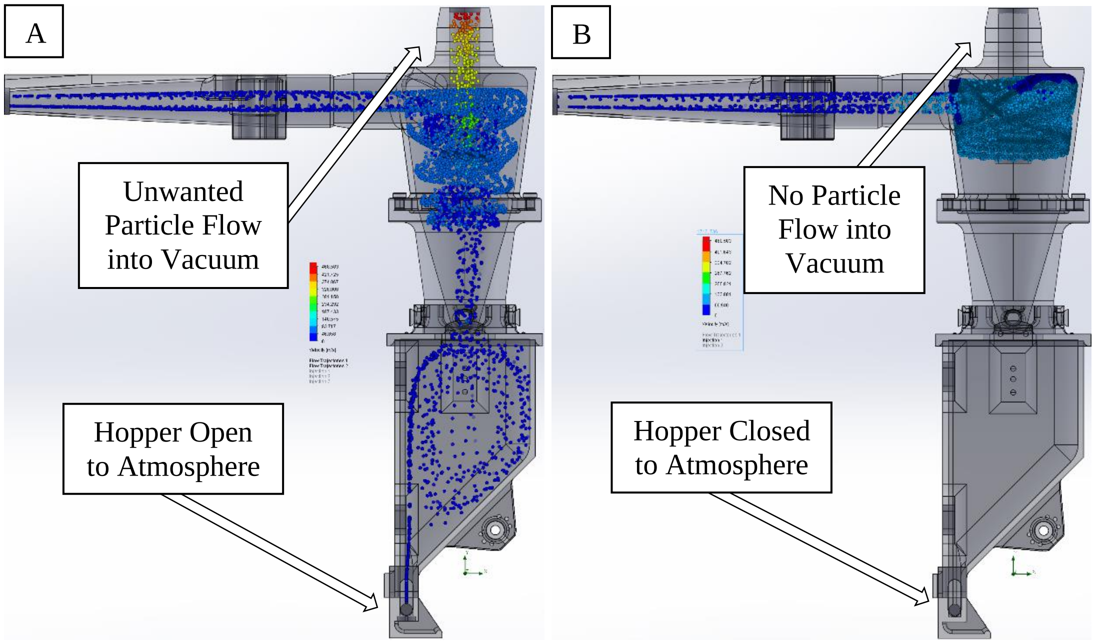


Figure 19. Cyclonic separator with particle injection simulation of open (A) and closed (B) hopper exit.

It was possible to move or jog a single-axis motor initially, such as just one of the two X1 axis motors, and all were checked for proper operation through their associated drives. Until multiple motors could be moved in parallel, each axis was only moved in very small amounts back and forth along the linear rails. Interfacing directly through the servo drives allowed for manual control of one entire axis at a time. This manual control allowed for slow operation to check the motion of the machine and home positioning. The X2 axis was moved back and forth with the hopper motor turned on and then with the roller motor turned on to represent powder dispensing and spreading.

5. NEXT STEPS

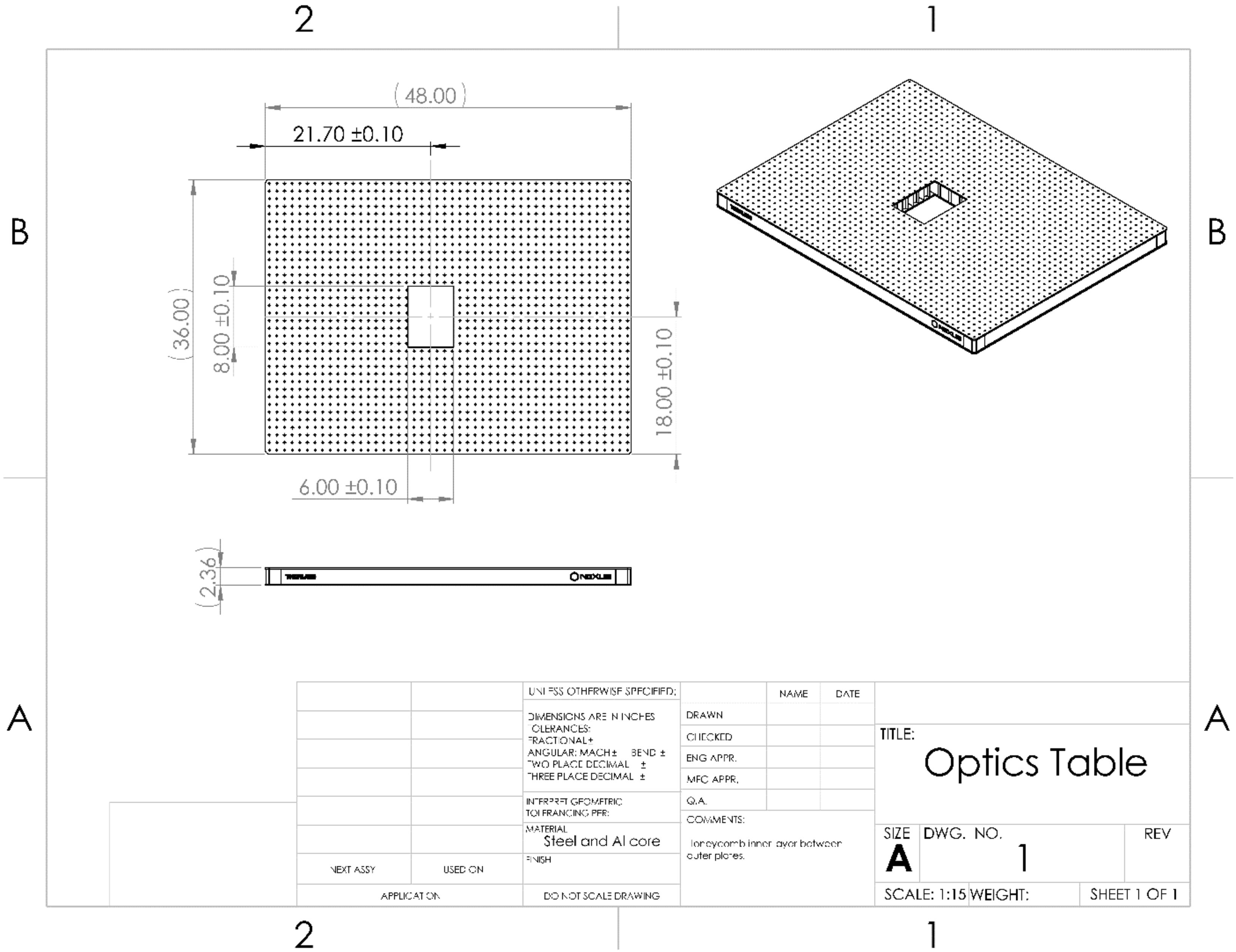
There are several aspects of the $BJAM^3$ machine that will need to be optimized for prototyping. One item to improve would be the user interface (UI) through the accompanying computer. The Lenze and Meteor controls could be combined into a single UI so that all process parameters such as spreading traverse speed, drying time, binder saturations, etc. could be changed during the build, along with displaying what 2D image, or slice, the print head will print so the operator can adjust settings on-the-fly. Process parameters will be recorded and stored for each material so that when an operator selects the materials being used, the printing process can be refined.

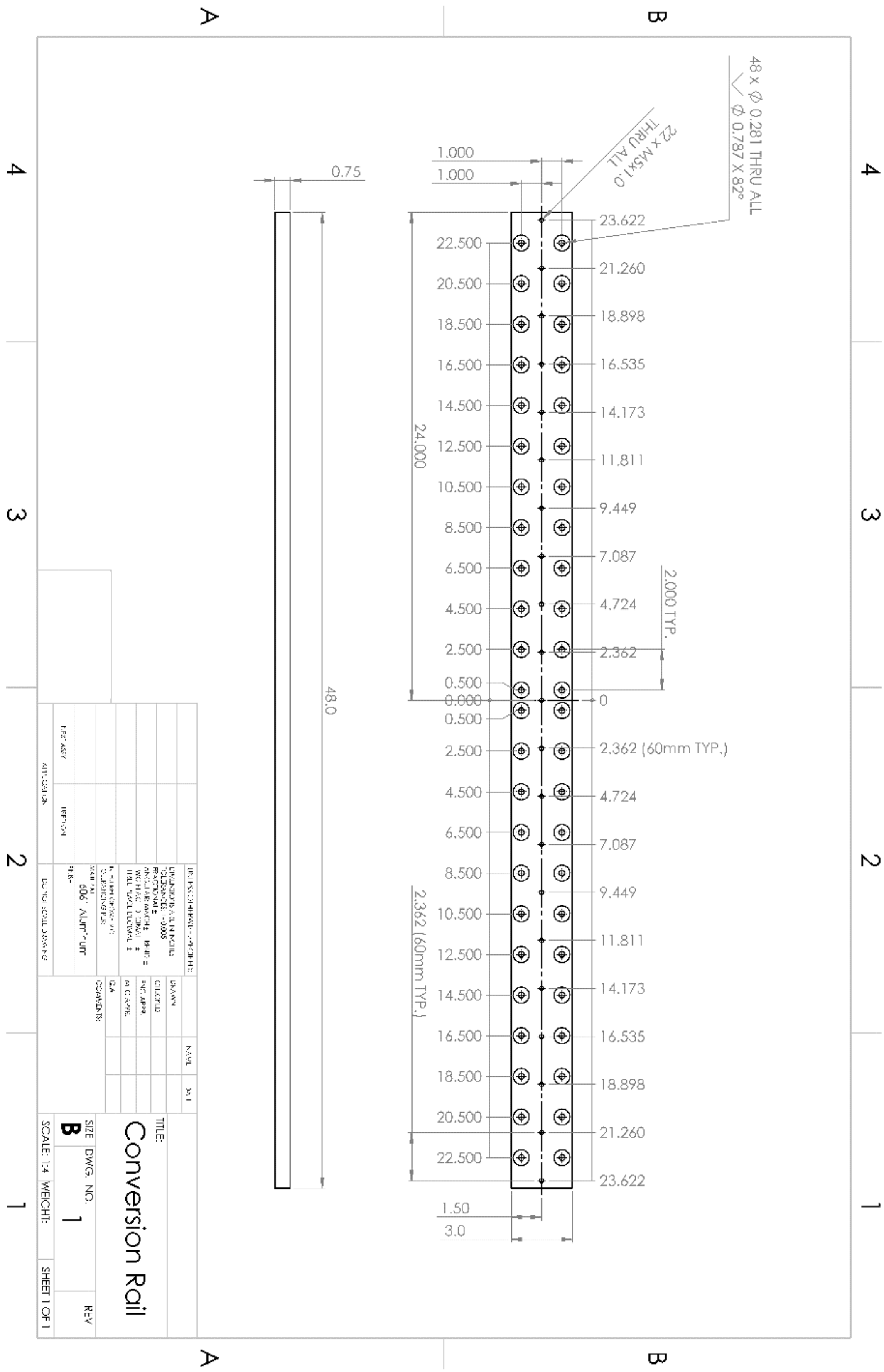
One stretch goal could be using additional sensors to record the entire digital thread related to parts. Sensors such as enclosure humidity, print bed temperature, hopper level sensors, and print head droplet cameras could be introduced to increase the recorded data during part manufacturing so that the entire production history could be available. Another future goal could be in-situ monitoring that uses infrared and visible light cameras or sensors to automatically evaluate and adjust process parameters.

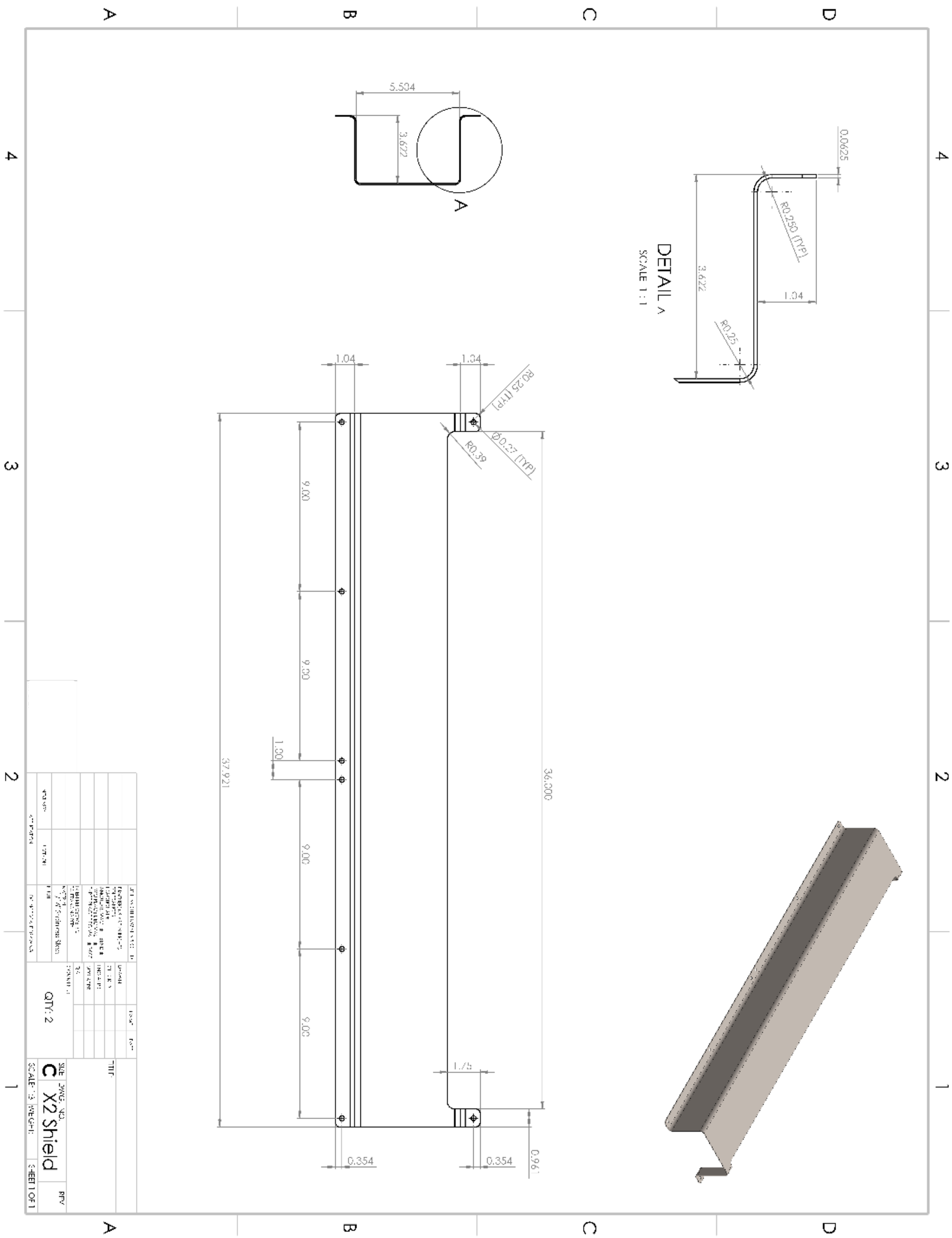
With the XAAR print head and Meteor equipment, multiple print heads or different binder combinations could be tested. As mentioned earlier, multiple print heads could be used to print larger swaths in one pass. The XAAR 1201 print head can be used in conjunction with others in rows to essentially create a much larger print head that could deposit a significant amount of binder in one pass, thereby reducing the number of passes required for the desired binder saturation. Multiple print heads could also be offset from each other, which would allow for one print head to deposit binder in one direction while the other print head could print in a perpendicular direction to ensure uniform binder deposition across the 2D area, as well as to reduce the number of passes. Each of the four rows on the 1201 has its own feed line, so multi-part binders could be tested without changing the powder feedstock as long as they meet the print head requirements.

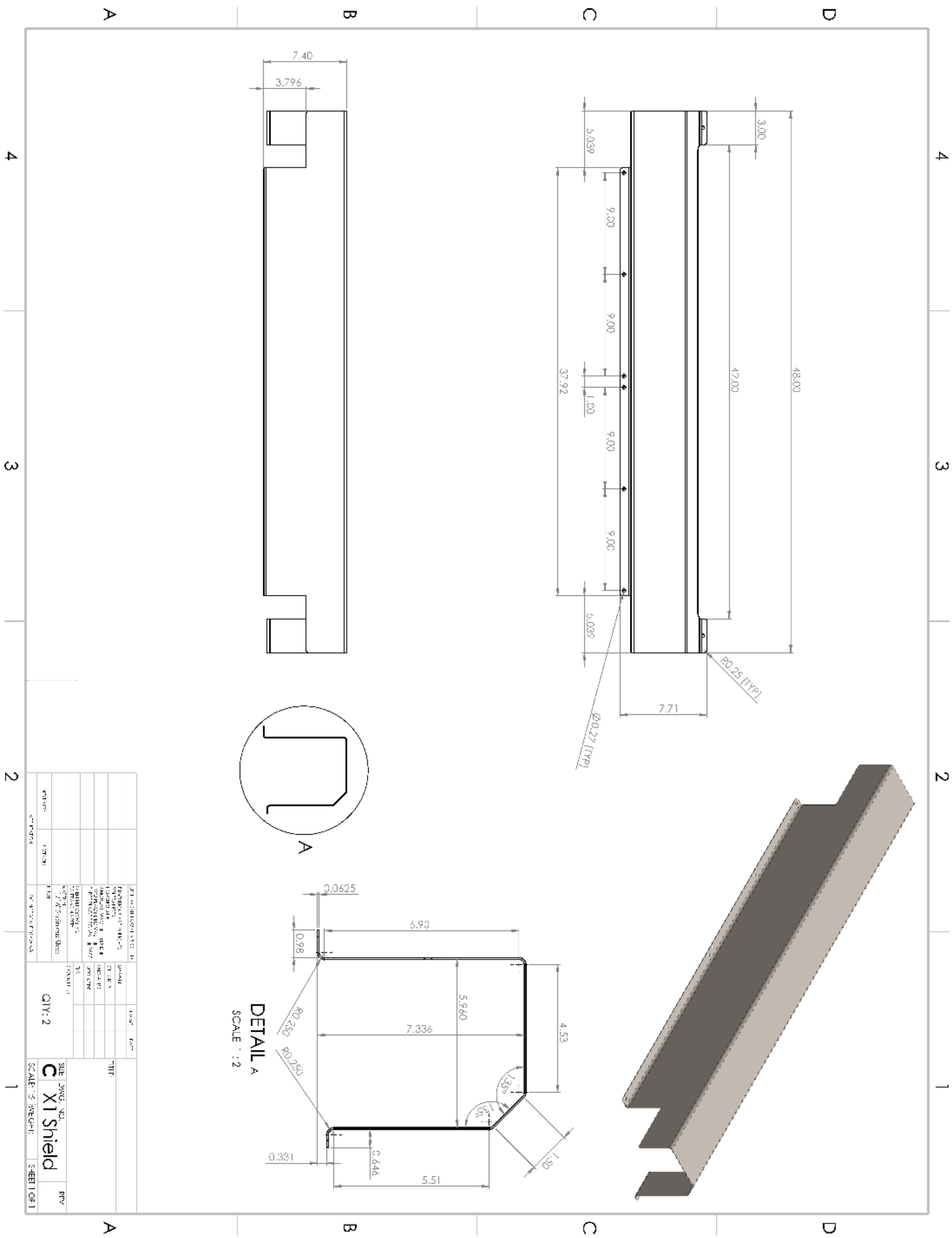
Once consistent settings have been developed, parts can be manufactured and evaluated. Complex geometries and parts requiring high accuracy can be produced in the green state with multiple materials and, after high-temperature furnace processing, material properties can be evaluated. Sintering behavior, microstructure, porosity, mechanical properties, and material interactions are all to be compared with existing available data.

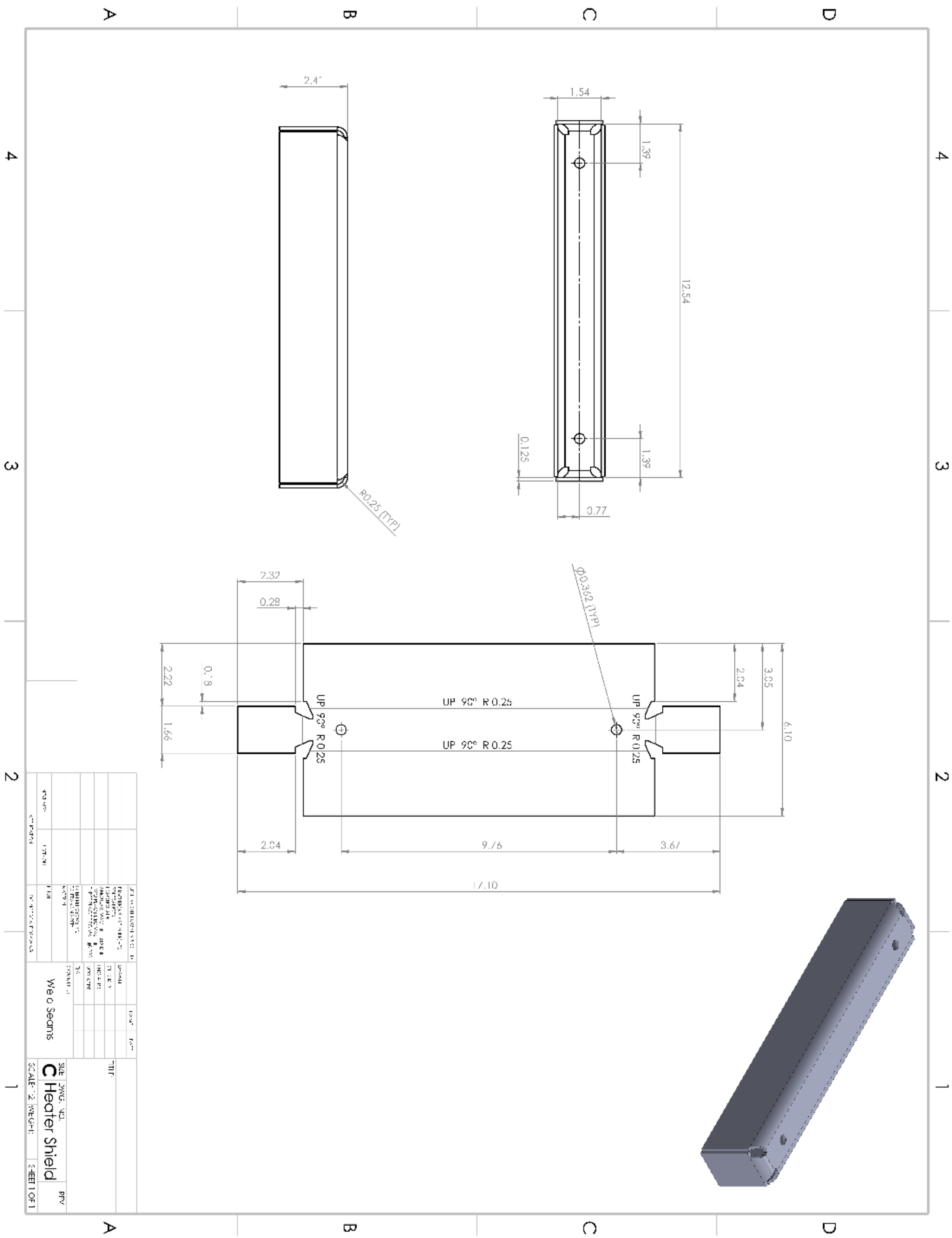
APPENDIX A: DRAWINGS


2
1
B
A
(48.00)
21.70 ±0.10
(36.00)
8.00 ±0.10
18.00 ±0.10
6.00 ±0.10
(2.36)
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Steel and Al core
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Honeycomb inner layer between outer plates.
TITLE:
Optics Table
SIZE
A
DWG. NO.
1
REV
SCALE: 1:15
WEIGHT:
SHEET 1 OF 1

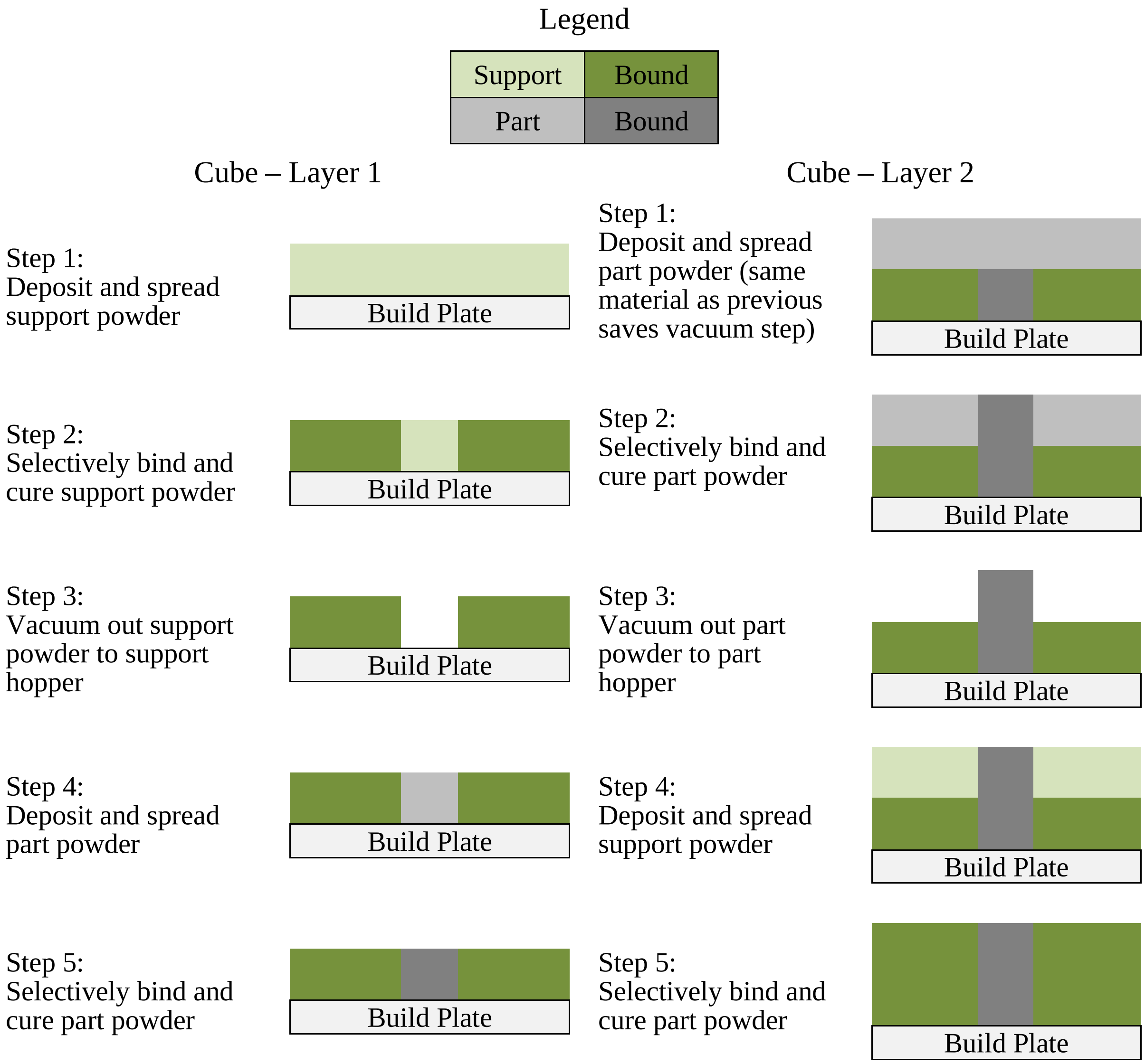

Conversion Rail
TITLE:
SIZE B
DWG. NO. 1
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
6061 Aluminum
48 x ⌀ 0.281 THRU ALL
⌀ 0.787 X 82°
22 x M5x1.0 THRU ALL
1.000
1.000
0.75
24.000
48.0
2.000 TYP.
2.362 (60mm TYP.)
1.50
3.0
22.500
20.500
18.500
16.500
14.500
12.500
10.500
8.500
6.500
4.500
2.500
0.500
0.000
0
23.622
21.260
18.898
16.535
14.173
11.811
9.449
7.087
4.724
2.362


5.504
3.622
A
0.0625
R0.250 (TYP)
1.04
R0.25
DETAIL A
SCALE 1 : 1
1.04
1.04
R0.25 (TYP)
R0.39
Ø0.27 (TYP)
9.00
9.00
1.00
37.921
36.000
9.00
9.00
1.75
0.354
0.354
0.961
QTY: 2
C
X2 Shield


7.40
3.796
3.00
5.039
9.00
9.00
37.92
1.00
47.00
48.00
9.00
9.00
5.039
R0.25 (TYP)
7.71
Ø0.27 (TYP)
A
0.0625
6.90
0.98
5.960
7.336
4.53
R0.250
R0.250
DETAIL A
SCALE 1 : 2
135°
135°
1.50
0.331
0.646
5.51
QTY: 2
TITLE:
SIZE
DWG. NO.
REV
C
X1 Shield
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1



2.41
1.54
1.39
12.54
0.125
1.39
0.77
R0.25 (TYP)
2.32
0.28
Φ0.362 (TYP)
2.22
0.78
1.66
UP 90° R 0.25
UP 90° R 0.25
UP 90° R 0.25
UP 90° R 0.25
2.04
3.05
6.10
2.04
9.76
3.67
17.10
Weld Seams
TITLE:
SIZE
DWG. NO.
REV
C
Heater Shield
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1


Legend
Support
Bound
Part
Bound
Cube – Layer 1
Step 1:
Deposit and spread support powder
Build Plate
Step 2:
Selectively bind and cure support powder
Build Plate
Step 3:
Vacuum out support powder to support hopper
Build Plate
Step 4:
Deposit and spread part powder
Build Plate
Step 5:
Selectively bind and cure part powder
Build Plate
Cube – Layer 2
Step 1:
Deposit and spread part powder (same material as previous saves vacuum step)
Build Plate
Step 2:
Selectively bind and cure part powder
Build Plate
Step 3:
Vacuum out part powder to part hopper
Build Plate
Step 4:
Deposit and spread support powder
Build Plate
Step 5:
Selectively bind and cure part powder
Build Plate