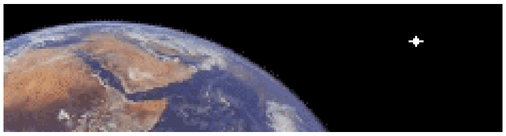


Rapid Product Development

Fused Deposition Modeling in Microgravity

June 2000

How will astronauts obtain replacement spacecraft parts en route to Mars and beyond? Rapid prototyping technology may provide the answer.

Introduction

Because of its manufacturing flexibility, **Solid Freeform Fabrication (SFF)** will be of enormous value to human exploration of space. Storing a large number of replacement parts on long-duration missions -- such as a journey to Mars -- is impractical, and waiting for replacement parts will not be an option. SFF has a number of potential advantages over traditional machining for use in a space-based manufacturing facility, but the reduced-gravity environment imposes a unique set of design constraints on SFF systems[1]. Besides materials, resolution, and throughput, additional considerations include equipment mass/complexity/power requirements, feedstock containment and handling, and the ability of a single machine to produce objects from multiple materials.

Deposition systems such as **Fused Deposition Modeling (FDM)** and **Shape Deposition Manufacturing (SDM)** are attractive candidates for meeting these challenges. Because they employ a very small melt volume that solidifies rapidly, these techniques are well suited to reduced-gravity operations. By adding particles to the feedstock (FDC/FDMet) and obtaining the final material properties in a second sintering step, a variety of materials can be deposited from a single piece of equipment. We have performed an initial evaluation of the potential for reduced-gravity manufacturing using a stock Fused Deposition Modeling system (Stratasys FDM 1600) as well as a fluid deposition system optimized for zero-gravity operations. These systems were flown on the NASA KC-135 Reduced Gravity Aircraft in preparation for an upcoming Space Shuttle experiment.

Liquid Handling in Reduced Gravity

Deposition of sheets of liquid is an extreme challenge in reduced gravity. The surface tension of the liquid will force the deposited sheet toward a geometry with reduced surface area; depending on the liquid and the surface, this could be a spherical drop or an unstable system, which breaks into many free-floating droplets. The key is to deposit liquid not as 2D sheets, but as a series of 1D beads that undergo rapid solidification after placement.

The spreading of a drop or bead is driven by reductions in interfacial energies, at a rate controlled by the viscosity of the liquid. A drop of liquid on a flat, rigid substrate will drive toward a sessile shape (spherical in zero gravity), stopping at an equilibrium configuration which minimizes the Helmholtz Free Energy of the system[2]. In the absence of gravity, this equilibrium configuration is defined by the **equilibrium contact angle,** determined from Young's Equation:

$$\gamma_{SV} - \gamma_{LV} = \gamma_{LV}\cos\theta$$

Where g represents the surface tension, or specific interfacial energy between the substrate-vapor (SV), the substrate-liquid (SL), and the liquid-vapor (LV), and q is the equilibrium contact angle that the drop makes with the substrate at the end of spreading. The driving force for spreading of a drop on a **self-similar** surface (as would occur in FDM) is a function only of the liquid's surface tension and current angle to the surface:

$$\gamma_{LV}(1 - \cos\theta)$$

The force of gravity is ignored in these equations, as surface tension is the overwhelming force in the spreading of small drops. The same is true for beads deposited in FDM processes. The dimensions of a deposited liquid below which gravity can be reasonably neglected is defined by the **capillary limit**[3], k.

$$\kappa^{-1} = \left(\frac{\gamma_{LV}}{\rho \bullet g}\right)^{\frac{1}{2}}$$

Where r is the density of the liquid and *g* is the gravitational constant. For materials associated with deposition systems, this limit ranges from about 1-5 mm. The diameter of FDM beads is below this, thus there should be little change in the shape between zero gravity and 1 g. NASA's Marshall Space Flight Center (MSFC) has recently performed a series of tests using a Stratasys FDM 1600 [**Figure 1**]. Objects were built with the machine on its side (perpendicular to the gravitational field) and upside down (counter to gravity). Visually, these objects were identical to parts built in the normal orientation.

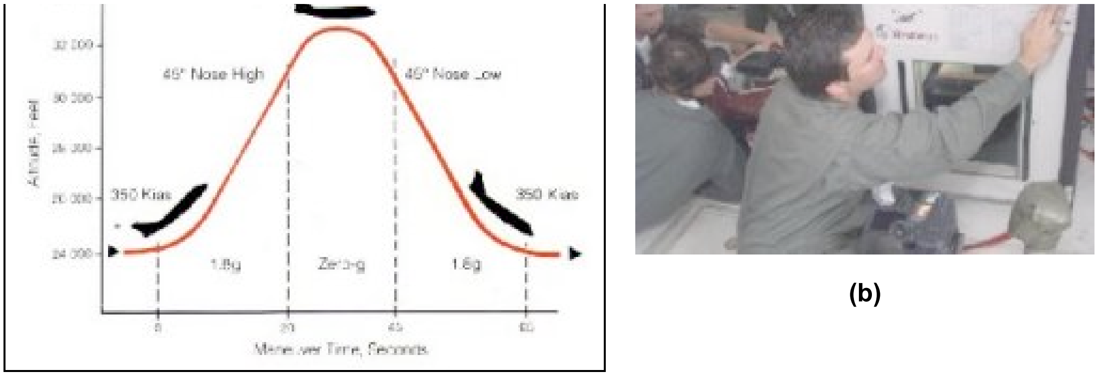
Figure 1. **Stratasys 1600 ground-based test, building parts perpindicular to gravitational field.**

The key to FDM in reduced gravity will be ensuring a continuous substrate (the previous layer). While surface tension is an effective force for spreading, it requires intimate contact with a surface. Above a certain tip height for a given bead diameter in an FDM process, the bead will tear due to unbalanced forces produced by the liquid surface tension. In 1 g, this can create flaws and gaps in the final part; in reduced gravity, the consequences are potentially more severe, as droplets will likely form and bead continuity will be lost. It has been proposed by one of the authors[4] that this is a similar geometry to the problem of an axisymmetric liquid bridge. The slenderness ratio of the tip height above the surface (l) divided by the diameter of the bead (d) must be below a height limit on the order of p to remain stable: $l < pd$.

Above this limit, high-surface-tension liquids are more susceptible to forming individual droplets. The force of gravity acts to stabilize the bead through minor *l* or *d* fluctuations during deposition (*e.g.,* head speed, tip height, flow rate). It is expected that continuous contact between the deposited melt and a solid surface will be critical without this stabilizing force.

KC-135 Reduced Gravity Aircraft Experiments

A Stratasys FDM 1600 was recently flown aboard the NASA KC-135 Reduced Gravity Aircraft [**Figure 2,** below]. The goal of these experiments was to obtain a set of initial qualitative observations on the feasibility of using FDM in a microgravity environment. Several ABS specimens of varying geometry were fabricated during a series of 160 parabolas, each of which provided nominally 25 s of reduced gravity. The geometry of the specimens allowed observations of inter- and intra-layer bonding, unsupported structures, and dimensional stability of specimens compared with the same designs fabricated in 1 g.



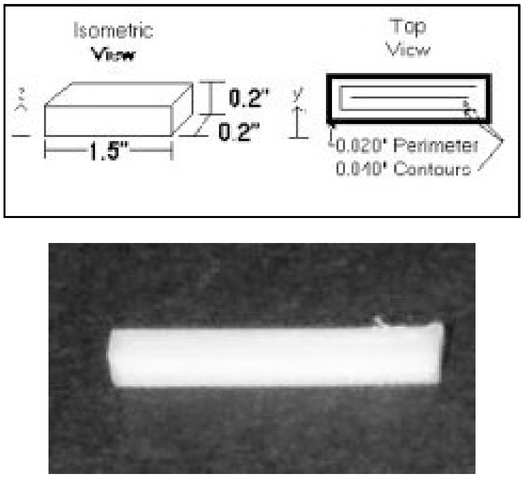
(a)

(b)

Figure 2. **(a) KC-135 aircraft trajectory (b) Stratasys 1600 during KC-135 reduced-gravity testing.**

Experiment Set #1: Continuous Substrate: Bars and Columns

Horizontal test bars were fabricated twice during the first flight, requiring approximately 10 parabolas each. Bars were fabricated using concentric extrusion paths, from the outside inward, until a solid part was achieved. Dimensions are shown in **Figure 3 (a).** Two vertical columns were fabricated during the remainder of the first flight sequence [**Figure 3 (b)**]. The columns consisted of a hollow box with 0.020" walls, with an operator-determined height of approximately 1".



(a)

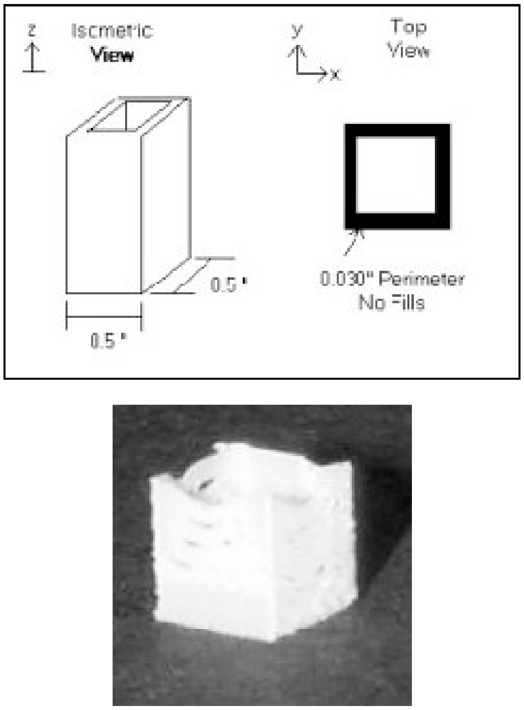


Figure 3. **Continuous substrate geometries and results: (a) horizontal test bar (b) vertical column.**

(b)

Intra-layer bonding between concentric extrusion paths was of interest for the horizontal test bars. If the absence of a gravitational force on the extruded beads reduced the magnitude of spreading or bead contact to the surface, the beads would be narrower than designed. This could cause delamination between the perimeters and contours, resulting in a series of unconnected concentric boxes as opposed to a solid structure. Results, however, were very much the same in microgravity as in 1 g. Both inter- and intra-layer bonding were good, and overall dimensions of the flight parts compared with the ground parts were: x = +/-0.00"; y = +/-0.00"; z = +/-0.00". It should be noted that, under normal conditions, the FDM deposition tip is designed to actually "smear" the material out to the required width (*i.e.,* $l < d$). The absence of gravity for this type of simple geometry deposited on a continuous substrate should thus not affect the properties of the final object.

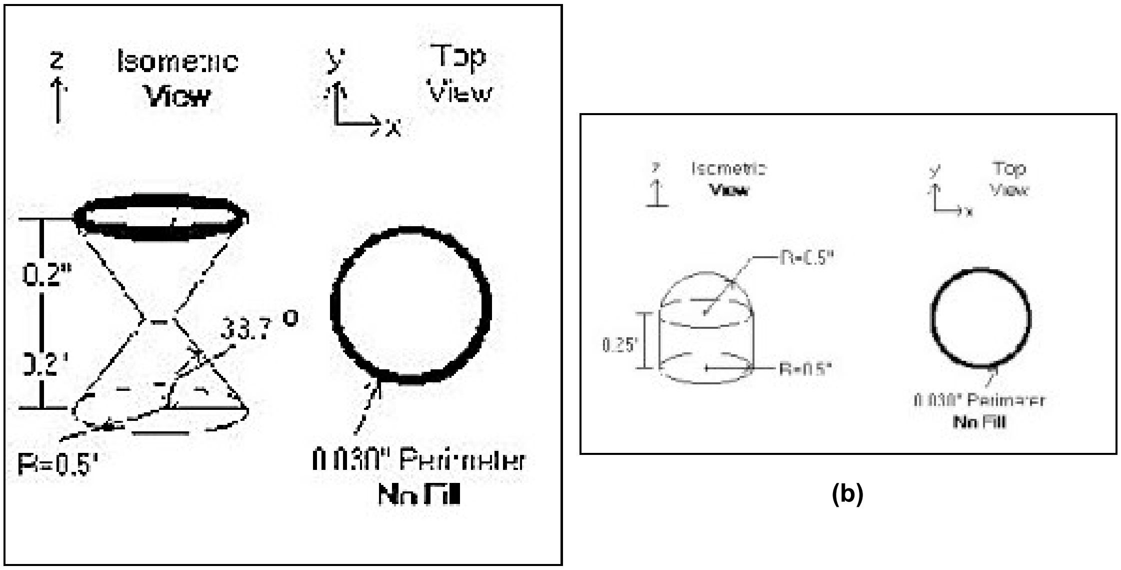
The vertical column was designed to verify the capability to build a tall, thin-walled structure in the absence of gravity. It was suggested that the thin walls would probably remain intact, however a taller structure may topple during a multi-g aircraft pullout. Although the structure remained intact during the pullout, the thin walls experienced a small amount of sag. Successive layers bonded only in areas where the previous bead did not sag (*i.e.,* bonding occurred only where there was a continuous substrate, generally at the corners). These failures continued to propagate throughout the remainder of the part, although it appeared that some process correction occurred during the zero-g segments of the flight.

Throughout these experiments, the FDM operated properly, holding to its designed patterns and extruding the proper volume of material. There was only one noticeable "side-step" during construction of the horizontal bar, resulting from one of the multi-g pullouts of the aircraft.

Experiment Set #2: Reduced Substrate: Hourglass and Dome

Geometries were fabricated that provided constant or increasing overhangs, reducing the substrate contact area for the successive layer. These geometries cannot be built in 1g without support structures. The hourglass design [**Figure 4(a)**] consisted of two blunted cones with 33.7° angles to the horizontal, connected vertically at their apex. This design prescribed that each consecutive horizontal layer was only attached to the previous layer by 25% of the surface area of the bead. The dome design [**Figure 4(b)**] consisted of a straight hollow vertical cylinder, capped by a constant radius dome. During fabrication in 1 g, this part failed (delaminated and slumped) near the upper 25% of the dome with a collapse induced by gravity.

It was assumed that the steep hourglass design and upper unsupported area of the dome would have a better chance at survival in zero g. Due to the extreme changes in cross section per layer at the tip of the dome, however, some failure was expected as a result of reduced substrate contact. It was also expected that the multi-g segments of the flight would possibly cause failure due to the weight of the overhanging structure.



(a)

(b)

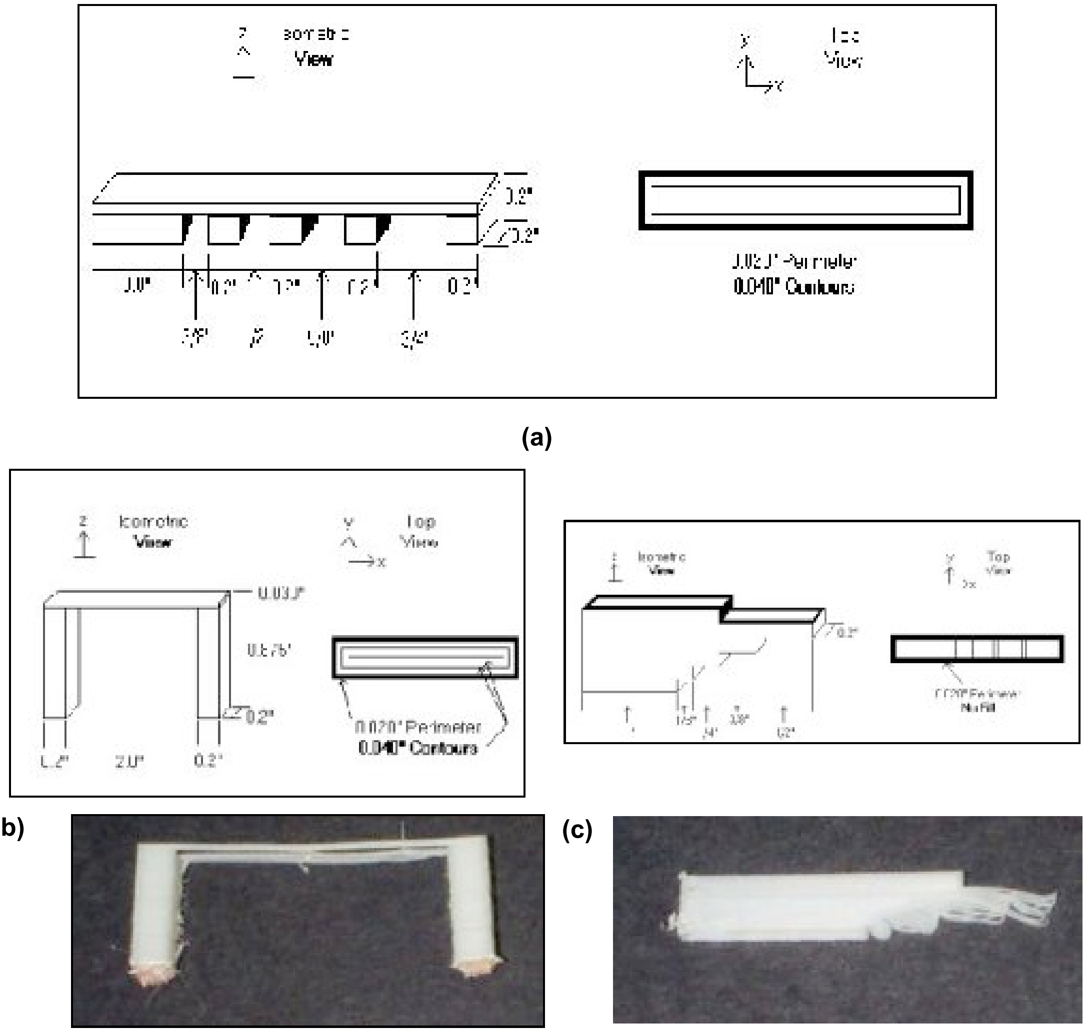
Figure 4. **Moderate overhang geometries: (a) hourglass (b) domed column (c) results (dome).**

(c)

As predicted, the hourglass did survive farther in reduced gravity compared with 1-g tests. Also as predicted, the multi-g flight segments caused a great strain on the excessive overhangs, causing a significant "waviness" to the once-horizontal layers. In the dome geometry, the horizontal layers in the cylinder and lower dome sections bonded properly. The cylinder radius was within +/-0.00" of the 1-g test. As per expectations, the hollow dome structure built higher more successfully than did its 1-g counterpart. These preliminary observations point to a potential reduction in support structures that will be required for fabricating components in microgravity, as long as minimum contact is provided with the previous layer. The FDM system performed properly during these experiments.

Experiment Set #3: No Substrate: Bridges and Cantilevers

A bridge-and-piers structure was fabricated at the beginning of the second flight day, during the first 10 parabolas. Several pier columns were built pre-flight at consecutively increasing horizontal gap spacings. The beginning pier was elongated to allow the material to reach its full flow volume before leaving contact with the substrate. Dimensions and specifications are shown in **Figure 5(a).** A second design, consisting of two tall vertical columns with a long span between them, was fabricated on the final flight day [**Figure 5(b)**]. Columns for this design were fabricated during the 1-g portion of the flight, and the span was fabricated in reduced gravity.



(a)

(b)

(c)

Figure 5. **Bridge and cantilever geometries and results: (a) Initial bridge with increasing spans; (b) modified bridge with tall vertical columns; (c) cantilever.**

The design in **Figure 5(a)** failed as expected when fabricated under 1-g conditions, with the unsupported bridge sections sagging down to the bottom of their corresponding voids. The flight test was to determine whether, at moderate head speeds, the rapid solidification of the thermoplastic would provide sufficient continuity between the initial substrate and the melt to allow extended unsupported deposition. Unexpectedly, the bridges sagged during reduced-gravity deposition to contact the lowest surface (the FDM foam platform), just as occurred in 1 g. It is likely that surface adhesion to the previous pier wall, in addition to frictional attraction of the foam platform, pulled the extruded beads down to this "undesired" substrate. Once in contact with the foam, it acted as the substrate for the remainder of the deposition. To avoid contacting the foam, the design in **Figure 5(b)** was used in successive experiments, with taller bridge piers acting to separate the span sufficiently from the base substrate. Results were positive in that the entire free span was connected by a smooth, horizontal bridge during the reduced-gravity segments of the flight.

The cantilever design [**Figure 5(c)**] was similar to the bridge-and-pier experiment, in that free-hanging "shelves" of consecutively increasing gaps were fabricated. In this case, however, the unsupported sections of the object had no second pier on which to attach. This design required that the extruded bead make a 180-degree turn in free space in order to return to the single supporting pier.

It was believed that the surface tension of the liquid would pull the soft, solidifying portion of the bead out of position during the about-face of the tip, destroying the desired geometry. Results showed that the horizontal layers of the solid part section bonded properly; however, those layers in free space did not: The unsupported segments did appear to "fall" some, as in the case of the bridge-and-pier. The turnaround and return of the tip indeed caused the free-hanging material to deform slightly, although the layers achieved moderate self-correction as the build progressed. Extremely unsupported structures such as this would most likely require a small amount of support in microgravity applications, due to the shear stresses imparted by the moving extrusion tip.

These experiments demonstrated that free spans of extended length can be fabricated without supported structures in microgravity, as long as: **1)** the head speed is sufficiently slow to allow solidification and maintain continuity with a "launching" substrate or pier, and **2)** there is a "landing" substrate, or secondary pier, on the opposing side of the void to be spanned.

One problem experienced throughout the test session was the effect of atmospheric humidity on the ABS build material. The build material is known to be moderately sensitive to the high humidity levels that were experienced in the test geographical area and season: Houston, TX, in June. This high air-moisture content caused the molten material to continue oozing from the extrusion tip long after it had been shut off at the end of a build layer. This would then cause a clump of material at the beginning of the following layer, along with a following gap as the flow caught back up to the ooze void in the extrusion tip. The result was a large, "fuzzy" build seam along the start points of each layer. A much dryer climate would be needed for follow-up testing conditions.

Space Shuttle "Get Away Special" Payload

The above tests were significantly limited by the affects of the multi-g segments of the flight during aircraft pullout. This was especially limiting on parts with overhangs. Further testing is required in an extended microgravity environment. Such testing is planned for a future Space Shuttle mission, on which a deposition experiment will fly as a shuttle "Get Away Special" (GAS) payload. Undergraduate students at the Milwaukee School of Engineering developed and constructed a mini-FDM to evaluate material flow and solidification [**Figure 6(a)**]. The hardware was tested on the same KC-135 flight as discussed in this article (test apparatus is visible on the left side of **Figure 2(b)**).

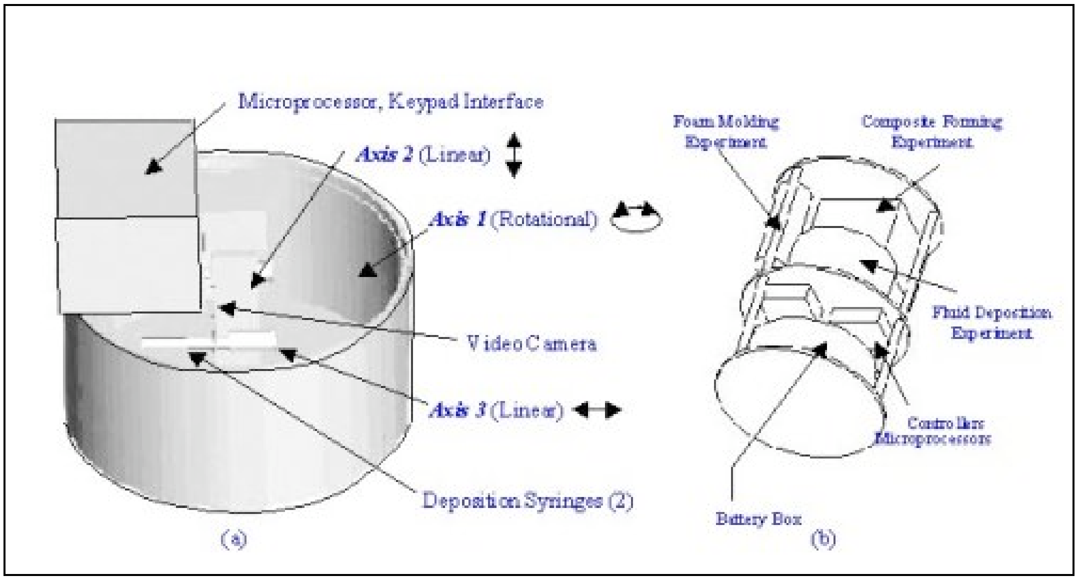


Figure 6. **(a) deposition apparatus (b) Get Away Special (GAS) experiment layout.**

The experimental apparatus consists of a 3-axis positioning system in cylindrical coordinates. Material is deposited on a rotating surface to provide the equivalent of ~25 linear inches of deposition real estate. Cameras are mounted to the dispensing head to provide a fixed, close view of initial deposition and material flow. This system uses standard, 25-gage Stratasys FDM tips and ABS plastic. Due to space limitations, however, the feedstock for the experiment is contained within a syringe (3cc) and is melted fully before extrusion. Eliminating all air from this large a melt volume is absolutely critical and has been a design challenge. Although the positioning hardware and data-collection systems performed well in the KC-135 tests, there will be some fluid-delivery system modifications based on lessons learned. The modified system will ultimately be repackaged into a NASA GAS container [**Figure 6(b)**], which must provide all power, control, thermal management, and data collection/storage for the experiments. In addition to the FDM apparatus, a set of composite forming and foam molding experiments will take advantage of the reduced-gravity environment to build complex freeform shapes without forms or mandrels.

The application of layered fabrication techniques is apparently feasible for standard and some non-standard part designs in a reduced-gravity environment. Further testing and development is planned to study the interaction between a deposited melt and substrate, as well as processing limits for free spans and partial substrates.

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References

[1] **K. Watson, D. Petersen, and R. Crockett,** "Application of Solid Freeform Fabrication Technology to NASA Exploration Missions"

[2] **P. Kralchevsky, A Dimitrov, and K. Nagayama,** "Analytical Expressions for the Shape of Small Drops and Bubbles," *Journal of Colloid and Interface Science* 160 (1993) 236-242.

[3] **A. Zosel,** "Studies of the Wetting Kinetics of Liquid Drops on Solid Surfaces," *Colloid Polym Sci* 271 (1993) 680-687

[4] **R. Crockett and P. Calvert,** "The Liquid-to-Solid Transition in Stereodeposition Techniques," in *1996 Solid Freeform Fabrication Symposium Proceedings,* Austin, TX: University of Texas at Austin (1996) 257-264.