



Microgravity Manufacturing Via Fused Deposition

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LIST OF ACRONYMS AND SYMBOLS

ABS	acrylonitrile-butadiene-styrene
ATP	authority to proceed
CAD	computer-aided design
CAE	computer-aided engineering
FDM	fused deposition modeling
GN ₂	gaseous nitrogen
ISPR	international standard payload rack
<i>ISS</i>	<i>International Space Station</i>
MSFC	Marshall Space Flight Center
MSG	microgravity science glovebox
N ₂	nitrogen
PDR	preliminary design review
RDR	requirements definition review
SCR	science concept review
SFF	solid freeform fabrication
TM	Technical Memorandum

TECHNICAL MEMORANDUM

MICROGRAVITY MANUFACTURING VIA FUSED DEPOSITION

1. SCOPE OF WORK

Manufacturing polymer hardware during space flight is currently outside the state of the art. A process called fused deposition modeling (FDM) can make this approach a reality by producing net-shaped components of polymer materials directly from a CAE model. FDM is a rapid prototyping process developed by Stratasys, Inc., which deposits a fine line of semimolten polymer onto a substrate while moving via computer control to form the cross-sectional shape of the part it is building. The build platen is then lowered and the process is repeated, building a component directly layer by layer. This method enables direct net-shaped production of polymer components directly from a computer file. The layered manufacturing process allows for the manufacture of complex shapes and internal cavities otherwise impossible to machine. This task demonstrated the benefits of the FDM technique to quickly and inexpensively produce replacement components or repair broken hardware in a Space Shuttle or *International Space Station (ISS)* environment. The intent of the task was to develop and fabricate an FDM system that was lightweight, compact, and required minimum power consumption to fabricate ABS plastic hardware in microgravity. The final product of the shortened task turned out to be a ground-based breadboard device, demonstrating miniaturization capability of the system (fig. 1).

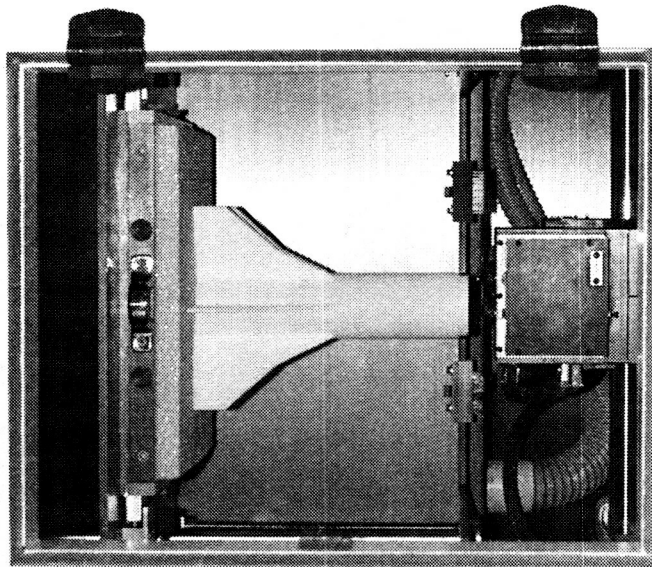


Figure 1. Fused deposition modeling system.

2. RELATED EFFORTS

The application of FDM to microgravity manufacturing has sustained some degree of preliminary testing through NASA Marshall Space Flight Center (MSFC). A commercial FDM unit was first tested by rotating the system onto its side and successfully building parts, free-hanging, against the pull of gravity. The ABS plastic components fabricated in this manner were comparable to parts fabricated in the upright position, which warranted further testing in the microgravity range.

In light of those results, the FDM system was tested on board the NASA KC-135 reduced gravity plane, and again yielded positive results. Seven geometries were successfully fabricated over a series of four flights, resulting in a total of ≈ 1 hr of zero-gravity flight time on the system. In fact, it was found during the flight testing that part configurations that required supporting fixtures during normal operation could be constructed freeform, or without supports, which eliminated the need for scrap support materials.

The next step will be to develop an FDM-type system to install on the Space Shuttle in order to examine long-term microgravity operation characteristics and functionality. The current smallest commercial FDM system, however, is still much too large and heavy for installation on a standard Shuttle middeck rack. The largest attachment capability, the double adapter plate, will have to be used even with a smaller modified FDM system.

3. SUMMARY

This Technical Memorandum (TM) documents a special study of the solid freeform fabrication (SFF) proof-of-concept hardware codeveloped by Ken Cooper (MSFC ED34); the apparatus was operated aboard the KC-135 aircraft in June 1999. The technical feasibility of developing an *ISS* experiment apparatus using this hardware or a modified design was assessed. Resource requirements for a potential *ISS* flight configuration were estimated and carrier options were examined.

Examination indicates that required revisions to the structural housing, lineage and qualification of components, and potential contaminant generation/control issues make modification of the KC-135 apparatus less effective than the development of an *ISS* dedicated payload design. Usage of some existing hardware may be possible, but this would likely be better applied to a requirements definition review (RDR) breadboard. Further discussion of recommended modifications is provided in this TM. Given the success of the KC-135 experiments and the enabling nature of this technology to long-term manned space missions, fabrication of a microgravity payload test bed apparatus as proposed by the development team is strongly supported.

Consideration of servicing and resource requirements indicates the best carrier option for an *ISS* design is probably an express rack. A microgravity science glovebox (MSG) configuration is potentially feasible, but will be complicated by the size of the apparatus. Installation of the proposed next-generation apparatus in an international standard payload rack (ISPR) is less desirable than an express rack location given the need for resources normally provided by express and the operational campaign planned for the test bed hardware. Shuttle middeck mounting is not considered viable due to recommended venting provisions. A Spacehab payload configuration for a dedicated research flight is physically possible but would likely not provide the operational time required for an effective experimentation program.

Maturity and demonstrated feasibility of the hardware concept support an accelerated schedule for development of an *ISS* flight configuration if so desired. Previous ground experimentation and analysis comprise much of the work typically required at the science concept review (SCR) level. The KC-135 hardware configuration is beyond the point typical of RDR breadboards. Documentation development is probably the critical path to an RDR; immediate attention to this is suggested. A potential development path from this point would be formation of a project team to formalize SCR-level documentation and proceed in 3-4 mo to an SCR. The RDR phase could likely be compressed to 7-9 mo with the goal of RDR-level documentation and preliminary design review- (PDR-) level flight hardware design at authority to proceed (ATP) level. Deployment of an *ISS* flight experiment within ≈ 2.5 yr appears feasible with an aggressive development program.

4. SOLID FREEFORM FABRICATION EXPERIMENT DESCRIPTION

SFF is an important developing technology that enables fabrication of any three-dimensional object directly from a computer data file; e.g., CAD data. The basic operation of any SFF system consists of slicing a three-dimensional computer model into thin cross sections, translating the result into two-dimensional position information, and using these data to control the placement of solid material. In the current process of choice, solidification occurs by deposition of molten material which solidifies upon cooling after a brief period of flow. This process is repeated for each cross section and the object is built up one layer at a time.

As the capabilities and materials amenable to SFF increase, these techniques are seeing increased application in manufacturing environments. SFF is currently used for the rapid production of visual models, low-run tooling, and functional prototype objects. Beyond these applications, the additive nature of SFF techniques offers great promise for producing objects with unique material combinations and geometries which could not be attained by traditional manufacturing methods. Examples of components built using SFF technology, shown in figure 2, include a carbon-fiber composite turbine blade, a zirconia oxygen sensor, hydrogel, alumina, silicon carbide, and silicon nitride houses. Sandia National Laboratories' thunderbird logos were prepared from alumina and Hershey's chocolate (lower left).

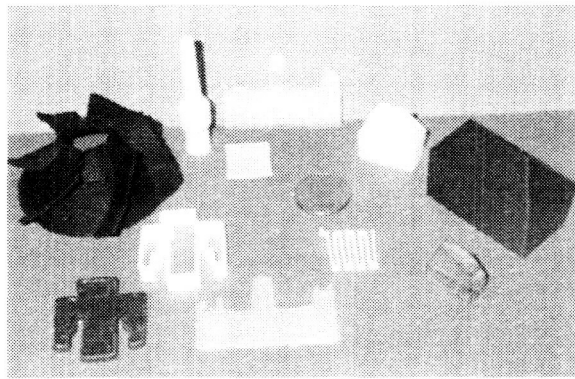


Figure 2. Range of objects produced by SFF deposition.

SFF has the potential to quickly create any object, in a variety of materials, without tooling or fixtures. Because of this manufacturing flexibility, SFF can be of enormous value to continued habitation of humans in space. NASA has established the value of SFF in reducing the cost and lead time of space flight hardware; laboratories at MSFC and NASA Johnson Space Center have been evaluating SFF technologies as a means of microgravity manufacturing. With moderate development efforts, SFF could serve the *ISS* as an on-orbit system for producing new and replacement components, as well as special purpose tools. Further out, it is reasonable to expect that SFF will play a key role in the in situ manufacturing support for a lunar base and/or missions to Mars.

5. SOLID FREEFORM FABRICATION HARDWARE DESCRIPTION AND KC-135 FLIGHT RESULTS

SFF experimentation using an apparatus derived from a commercial system design was performed in June 1999 aboard a KC-135 research aircraft. Results from the flight program and ground investigations were successful in demonstrating both feasibility of the technique in reduced gravity and the need for further research in an environment providing extended microgravity duration.

Commercial systems sold by Stratasys, Inc., are currently operational in the MSFC Rapid Prototyping Laboratory; these units are shown in figure 3. A turbine blade model under fabrication from ABS plastic is visible in the left unit.

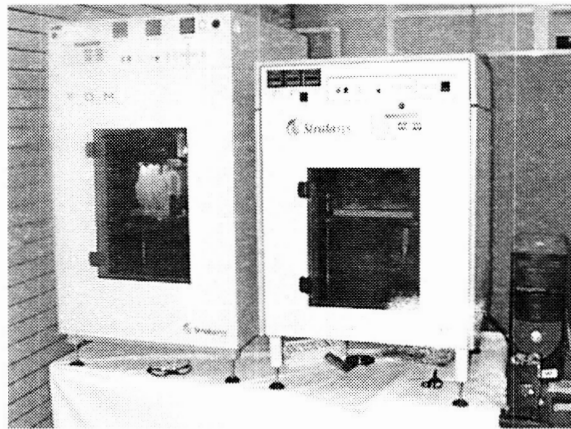


Figure 3. Stratasys, Inc., SFF units in operation at the MSFC Rapid Prototyping Laboratory.

Hardware configurations of the commercial and KC-135 units are similar. The part under construction is built on a flat stage. The stage is lowered in ≈ 0.01 -in steps over the course of the build cycle by a motor system. The heart of the apparatus is the deposition module shown in figure 4. The module uses a motor to drive rollers feeding plastic filaments (similar to Weed Eater[®] line) into a heated “melt tube.” The molten material is extruded through a nozzle at the other end of the tube onto the part being constructed. The module shown uses twin extrusion systems that allow fabrication of components from two different feedstock materials.

The deposition module is carried on a precision X-Y translation table controlled by stepper motors similar to that driving the assembly stage. An internal controller orchestrates the movement of the system and the extrusion of the build material based on inputs from an external computer system.

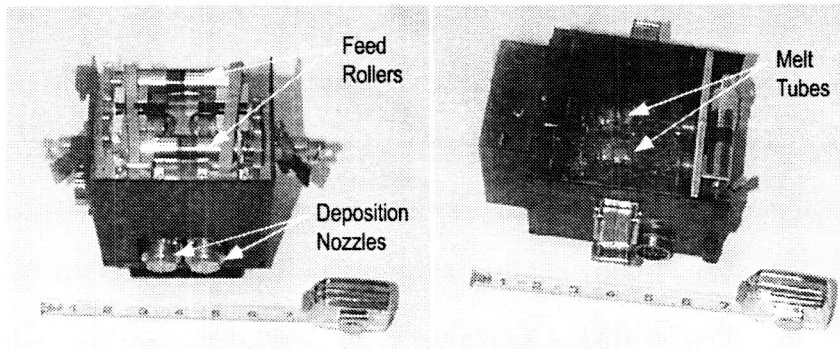


Figure 4. Deposition module from Stratays, Inc., SFF system.

The KC-135 experiment apparatus is shown in figures 5 and 6, and is basically a commercial unit optimized to reduce weight and meet interface requirements of the KC-135 aircraft. Characteristics of the KC-135 hardware are:

- Weight: 118 lbm.
- Dimensions: 18 by 21 by 22 in.
- Power: 120 V ac, 150 W maximum, >75 W average.

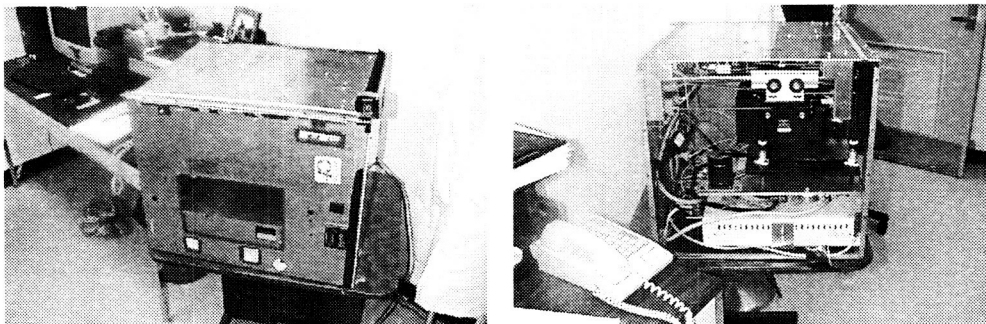


Figure 5. MSFC-Stratays, Inc., SFF apparatus flown on the KC-135 aircraft.

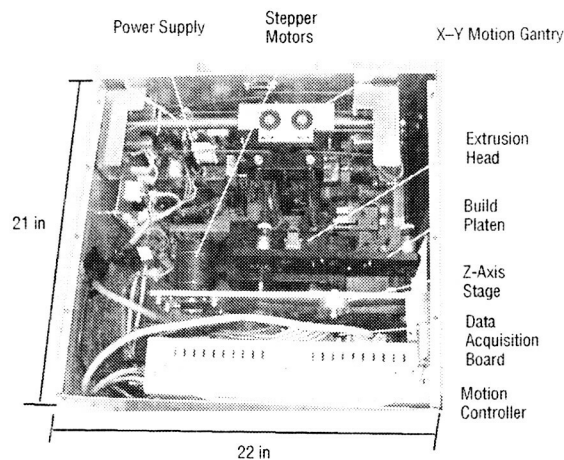


Figure 6. MSFC-Stratays, Inc., SFF apparatus internal detail.

6. INTERNATIONAL SPACE STATION EXPERIMENT HARDWARE IMPLEMENTATION CONSIDERATIONS

Development of an *ISS* experiment configuration for the SFF appears feasible with no major technical challenges. There are several aspects of the apparatus and the proposed investigation which should be considered with respect to an *ISS* application. These include:

- (1) Contaminate generation: The materials of choice for an *ISS* SFF test bed are plastics. A materials analysis performed by MSFC generated an "A" rating for the ABS plastic used on the flight, but also noted that it failed to meet the 0.5 toxic hazard index value requirement of NASA-STD-6001. While the commercial Stratasy, Inc., hardware is intended for office environments, the facility users noted that it does produce a discernable odor during operation. To preclude future safety compliance issues, isolation of the fabrication chamber from the *ISS* cabin environment appears a good design approach. Additionally, the KC-135 experiments noted sensitivity to humidity levels during operations; the developers have proposed a sealed nitrogen (N₂) environment as a solution to this problem. Gaseous nitrogen (GN₂) and vacuum interfaces are a standard service of the express rack. Implementation of a simple vent/purge design for the processing chamber is recommended.
- (2) Camera system: An internal ground-commandable camera system is needed to support the *ISS* experiment implementation. This system should be integrated into the experiment design.
- (3) Crew time issues: Given the known constraints, system design for semiautonomous operation should be emphasized for the *ISS* hardware.
- (4) Control system: The complexity of the desirable command/control capabilities justifies consideration of a dedicated computer system as part of the flight configuration. A PC/104 or similar system is suggested. Direct ground control for the input of configuration files and real-time adjustments to the hardware operational parameters would be advantageous to maximizing science return and reducing crew loading.
- (5) Increased fabrication volume: An approximately 4- by 4- by 4-in fabrication volume was proposed for *ISS* application in the documentation reviewed. The feasibility of increasing this volume should be considered so as to potentially allow fabrication of larger items on the *ISS*, should the need arise, during SFF test bed flight operations. The availability of this resource could impressively demonstrate the utility of the hardware.
- (6) Qualification of components: Adaptation of the existing KC-135 apparatus for *ISS* duty has been suggested as a cost-saving and schedule-reduction measure. While not ruled out entirely, the cost of qualifying the existing hardware in combination with potential reliability risks would likely preclude this approach. Development of an *ISS*-specific experiment design is recommended as a better approach which could allow implementation of these considerations.

7. INTERNATIONAL SPACE STATION PAYLOAD SUBSYSTEM BREAKDOWN AND RESOURCE ESTIMATES

Based on the KC-135 hardware, the documentation provided, and the considerations described in section 6, the following major subcomponents would comprise an SFF *ISS* payload configuration:

- (1) XYZ translation table system.
- (2) Fluid deposition module with heaters and motors.
- (3) Ground commandable data acquisition, command, and control system.
- (4) Close proximity camera system.
- (5) Structural support enclosure with sealed processing chamber.
- (6) Vent/purge gas control hardware.
- (7) Manual operational interfaces for crew use.

The following *ISS* payload resource estimates are submitted:

- (1) Weight: 100–150 lbm.
- (2) Power: 300 W maximum, <150 W average.
- (3) Thermal: 150 W, air cooling feasible.
- (4) Vacuum: vent interface for dump/purge of internal atmosphere.
- (5) GN₂: desirable for processing chamber purge, could use cabin air instead of N₂.
- (6) Command/control: dedicated experiment processing system appears justified. Capability should include uplink of fabrication data files and real-time operational commands. Real-time downlink of experiment video is desirable.
- (7) Physical envelope: comparable to KC-135 apparatus (18 by 21 by 22 in).

8. INTERNATIONAL SPACE STATION/SHUTTLE CARRIER OPTIONS

Potential carrier platforms were assessed for compatibility with the derived SFF requirements. These were the MSG, express rack, an ISPR, Shuttle middeck, and Spacehab rack. Based on the assumed requirements for crew loading/unloading of parts and a pressurized operating environment, locations external to the *ISS* habitable volume were not considered.

The draft proposal for the experiment suggests the first SFF orbital apparatus will function as a test bed for a later rack or half-rack unit providing Station maintenance support. A desire for rapid deployment of the test bed naturally suggests the express rack or MSG as the carriers of choice for the *ISS*. Integration as a rack- or half-rack-level payload in an ISPR was considered but is probably not an effective use of *ISS* resources. If an approximately one-fourth-rack space were available on a currently manifested rack, this may be an option.

Examination of MSG interface requirements shows that the physical envelope of the KC-135 apparatus is incompatible with the 16-in depth of the MSG working volume and the MSG 16-in-diameter pass-through port. Reconfiguration of hardware to allow MSG mounting may be feasible but requires additional study. Use of the MSG might eliminate the need for sealing the processing chamber if contaminant generation can be controlled with an appropriate filter media. Further assessment to weigh the advantages of an MSG versus rack implementation should be part of the initial development effort.

An 8-2 express rack carrier appears to satisfy the SFF interface requirements. In this configuration, the experiment would occupy a double locker position. The standard express provisions for avionics cooling, GN_2 , and vacuum service would simplify development and integration versus an ISPR option. Attention to express rack load capabilities will be required; the current KC-135 hardware is near the capacity of a double locker allocation.

Manifesting on a dedicated Shuttle research mission was also examined. Based on lack of vent/purge resources, flight in the Shuttle middeck does not appear feasible. Integration in a Spacehab single or double rack is a viable manifesting option if mission duration were long enough to satisfy the experimentation goals. Review of the draft science proposal indicates that the iterative study methodology planned would likely not be supported in the timeframe of a dedicated Shuttle flight.

9. SCHEDULE ESTIMATE

An accelerated development schedule is viable for the SFF payload. The draft science proposal suggests a 4-yr program, with development and ground testing in the first and second years, flight in the third year, and postflight assessment in the fourth year. This appears to be a workable schedule given the advanced nature of the hardware development and the successful KC-135 campaign.

The suggested approach for a development schedule would be an early SCR of the experiment objectives and hardware configuration, followed by an accelerated RDR phase. Assuming a 1.5- to 2-yr duration from ATP to flight, RDR must be reached in ≈ 1 yr to support flight in the third year of the program. Following proposal acceptance, an SCR could probably be supported within 3 to 4 mo. With the current hardware concept maturity, development of documentation will likely be the greatest challenge to supporting an RDR. It is likely the hardware design could be solidified near the PDR level by RDR; this would facilitate continued acceleration of the schedule if so desired.

10. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made:

- (1) SFF has significant potential as an enabling technology for long-duration manned space flight. Rapid development of an *ISS* flight experiment is supported.
- (2) Repackaging the KC-135 hardware for *ISS* use is less desirable than a clean slate approach.
- (3) Reduction of crew time requirements is desirable and possible with an enhanced control system. Addition of a PC/104 stack or similar system supporting semiautonomous operation and enhanced control from the ground appears to present significant benefits.
- (4) Implementation of a dedicated camera system and a vent/purge capability for the processing chamber should be included in an *ISS* configuration.
- (5) An express rack appears to be the best choice for *ISS* flight, but further study of an MSG option is recommended. Hardware mass must be minimized to remain within express rack load capability.
- (6) Manifesting on a dedicated Shuttle research flight is not a desirable option due to the iterative nature of planned experimentation.
- (7) An accelerated development schedule is feasible based on the maturity of the hardware concept and past experiment success.

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