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Design for Additive Manufacturing

Manufacturing Design & Technology

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1 Introduction

The international space station (ISS) stands as a triumph of human engineering, and as one of the most demanding environments in existence. Every module and component must be launched from Earth, with an estimated price per kilogram of \$1,500 (Jones, 2023), and part manifests planned months or years in advance. As human spacefaring interests shift to Lunar and Martian colonisation, the limitations of an Earth-dependent supply chain become increasingly apparent, making the case for manufacturing of components in space increasingly attractive.

Additive Manufacturing (AM) offers a potential solution to these constraints. The manufacturing of components on demand from digital designs removes the need for spare parts, thereby reducing resupply cargo mass and volume, and permitting geometries of greater complexity than afforded by traditional subtractive and formative manufacturing methods. The ISS has demonstrated the potential for AM (Figure 1) in microgravity through the Additive Manufacturing Facility (AMF), since its installation in 2016, it has produced over 200 components in Orbit. Further, a 3D metal printer installed in 2024 (ESA, 2024) on the ISS by the European Space Agency (ESA) has successfully produced metal components in orbit.

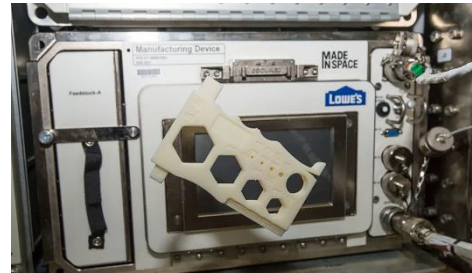


Figure 1, AMF printer operating on the ISS, IEEE (2018)

This report presents a Design for Additive Manufacturing (DfAM) case study on a personalised ventilation (PV) air diffuser nozzle for use in the ISS Crew Quarters (CQ). The component was selected because it addresses a critical and well documented problem, accumulation of CO₂ in the astronaut's breathing zone, with a geometry whose ideal form is impossible to manufacture by conventional means.

The report analyses current CQ ventilation systems and their limitations, details the mechanisms of accumulation of CO₂ in microgravity, defines design specifications, documents the DfAM redesign process, justifies the manufacturing process and material selection, and critically evaluates the challenges associated with in-space manufacture. Each section builds upon its predecessor, the performance limitations identified in Section 2, and the physical mechanisms described in Section 3 influence the design specification in Section 4, which constrains the redesign of Section 5. The AM process justified in Section 6 is limited by the operational environment established in Section 2, and the evaluation in Section 7 contextualises design decisions within the logistics and economics unique to the ISS.

2 Background

2.1 System Architecture

The CQs aboard the ISS are located within the Harmony module and have been operational since 2008 (Broyan and Cady, 2010). Each CQ provides a private compartment for sleeping and personal space, within a standard rack with a volume of approximately 2.1 m^3 . As opposed to other ISS modules, the CQs are not interfaced with the liquid coolant loops present on the ISS, relying instead on-air exchange between CQs and the Harmony module aisleway for thermal regulation.



Figure 2, ISS Crew Quarters Interior, Sherwood (2011)

Each CQ relies on a push-pull fan configuration with two axial fans mounted in series for redundancy; to mitigate the risk of asphyxiation, should a fan fail during sleep. Air is routed through a duct from a protrusion in the Harmony module hallway into the CQ. Due to limited space, the duct network has multiple path changes. Despite this, the cross-sectional area of the duct remains at approximately 120 cm^2 . The fan rotation speed can be varied to supply one of three flow rates: 108, 138, and $156 \text{ m}^3/\text{h}$.

2.2 Known Limitations

The existing diffuser is a flat louvred grill in a 1×4 array of rectangular regions. The duct airflow is split into 4 equal channels, each delivering airflow to one grille, allowing for a low direction bias diffusion of airflow into the CQs interior. Several issues are documented in literature, at the lowest fan setting ($108 \text{ m}^3/\text{h}$), the fan failure alarm triggers occasionally due to accumulation of dust in the ventilation ducts lowering the flow rate (Georgescu et al., 2021). Noise complaints have been filed when the fan runs at the highest setting ($156 \text{ m}^3/\text{h}$). This creates an operational window in which the ventilation system can either be insufficient in flow rate, or audibly bothersome.

Critically, the existing solution cannot deliver targeted airflow to the astronaut's breathing zone. Georgescu et al. (2021) combined investigation established the breathing zone in microgravity as a region 4cm wide and extending 11cm from the astronaut's nose. Even with the CQ ventilation system active, carbon dioxide (CO_2) concentrations in the breathing zone are greater in microgravity than

under terrestrial conditions, demonstrating that current ventilation applications do not effectively address the localised accumulation issue.

From an acoustic standpoint, Broyan and Cady (2010) documented that acoustic mitigation accounts for 13% of the total CQ volume, and 6% of the total CQ mass. Acoustic treatment is applied externally to ducts and fans as foam panel installations, a solution necessitated by the higher flow rates required of a non-specific ventilation system, and limitations in conventional manufacturing methods. This mass and volume overhead is directly addressable through DfAM.

3 CO₂ Accumulation in Microgravity

In attempting to justify the design decisions, an understanding of why CO₂ accumulates around an astronaut's face and why it is not easily remedied by conventional ventilation is crucial. The root cause is the elimination of the Human Thermal Body Plume (HTBP) in microgravity.

On Earth, the human body's approximate 37°C core temperature is almost always warmer than surrounding air, driving buoyancy-induced convection. Warm air adjacent to the skin rises continuously, generating an upward thermal plume, flowing from the feet, over the torso, and around the head. This plume continuously carries exhaled CO₂ away from the breathing zone. Porterfield et al. (2026) demonstrate this using CFD,

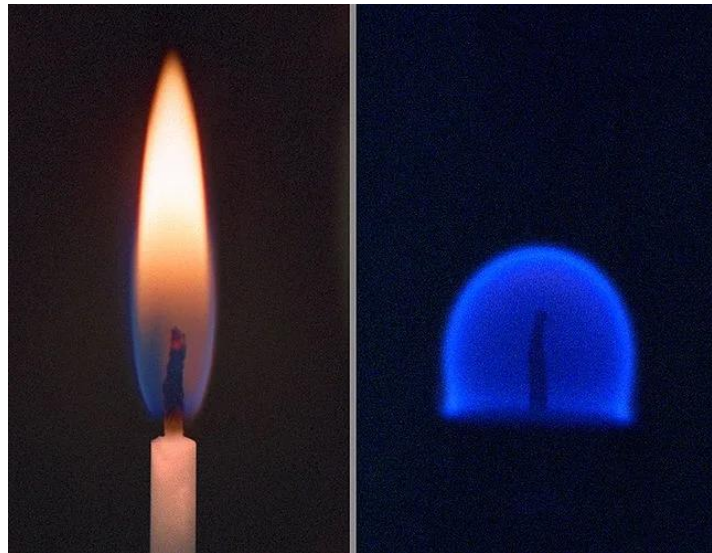


Figure 3, Flame in Earth vs in microgravity, ScienceCasts (2013)

showing that HTBP generates airflow around the human body that facilitates effective respiratory gas exchange. Their candle flame analogy illustrates how on Earth buoyancy sculpts a flame into a teardrop that continuously carries combustion products upwards. In microgravity, the flame spreads spherically and stagnates at the source.

The same phenomenon applies to the human body. In microgravity, the HTBP cannot form as there is no preferred direction for warm air to rise toward. Exhaled CO₂ therefore disperses isotopically from the nostrils, forming a stagnant pocket around the mouth and nose that grows with each breath. Without the shear flow of the HTBP to continuously remove exhaled gas, molecular diffusion alone enables dispersion. CO₂ diffuses through still air at approximately 16mm²/s, too slowly to clear the breathing zone between breath cycles of approximately 4 seconds.

The consequences are significant, Dutta et al. (2026) describe this as an environmental breathing deadspace, immediately in front of the face, leading to significant CO₂ rebreathing. Further, ISS CO₂ concentrations average at 0.5%, ten times higher than terrestrial ambient levels, and concentrations in the BZ substantially exceed this. The key insight for nozzle design is that bulk flow rate is not the

primary solution variable, targeted delivery of turbulent fresh air to the BZ is effective in clearing the deadspace, as confirmed by Georgescu et al. (2021)

4 Design Specification

A design specification was established prior to undertaking the redesign, drawing upon functional requirements and constraints found in Sections 2 and 3.

4.1 Functional Requirements

4.1.1 Airflow Targeting

The nozzle will deliver fresh air laterally to the astronauts breathing zone, in line with the lateral PV configuration demonstrated to be most effective by Georgescu et al. (2021). The lateral configuration is specified on the basis that a frontal placement resulted in contamination of the air within the diffuser during human exhalation. CO₂ concentration reduction in the BZ is identified as the primary performance metrics for PV systems of this type. Quantification is beyond the scope of this study, but the design basis is established by validated CFD results reported by Georgescu et al. (2021)

4.1.2 Exit Velocity

Mean exit velocity at the face surface must not exceed 0.6m/s. Above this, human subjects reported uncomfortable draught sensations as reported by Bolashikov et. Al (2013). Occupant comfort in ventilation design is evaluated using the Draft Rate (DR) metric defined in EN ISO 7730 calculated as:

$$DR = (34 - t_{a,l})(\bar{v}_{a,l} - 0.05)^{0.62}(0.37 \cdot \bar{v}_{a,l} - Tu + 3.14$$

where

$t_{a,l}$ is the local air temperature in degrees Celsius

$\bar{v}_{a,l}$ is the local mean air velocity, in metres per second

Tu is the local turbulence intensity, in percent.

A key design consideration in the literature is that turbulence intensity appears both in the DR formulation, and the CO₂ boundary layer disruption mechanism, such that increasing the effectiveness of disruption increases the intolerability of DR. Any future optimisation must therefore balance these variables.

4.1.3 Turbulent Kinetic Energy

The redesigned nozzle should maximise Turbulent Kinetic Energy (TKE) at the breathing zone, as this is the primary mechanic by which CO₂ deadspace can be disrupted in microgravity. As established in Section 3, molecular diffusion alone cannot clear the breathing zone, directed flow with sufficient

turbulent shear is a necessity. The literature identifies TKE at the face as the key metric for comparison between PV diffuser geometries. TKE evaluation is beyond the scope of this study, however, the six-lobed hemispherical geometry is selected on the basis that it has been demonstrated to generate superior TKE relative to alternatives at equivalent flow rate.

4.1.4 Component Consolidation

The mounting interface, supply tube, and nozzle shall be consolidated into a single printed assembly to maximise component consolidation and mitigate complications with airtight seals.

4.2 Manufacturing Constraints

The component must be manufacturable within the AMF's 152x152x152 mm build envelope, using compatible feedstock.

Internal features must be designed to minimise unsupported span lengths. Unsupported spans in microgravity FFF are subject to thermal deformation, surface tension effects on long spans, and lateral displacement by print head drag.

4.3 Operational Constraints

The nozzle shall operate at 1m³/h PV flow rate, in line with the validated configuration from Georgescu et. Al (2021), without exceeding the available pressure drop being diverted from the crossflow fan PV circuit. It should be noted that this figure is derived from the flow rate measured at the PV circuit outlet from Georgescu's et al. study (2021).

All materials must comply with FAR 25.853 aircraft interior flammability requirements, due to the pressurised habitable environment. It is worth noting that FAR 25.853 is an aircraft standard, and was selected as there is no applicable standard available that is ISS specific, it simply serves as an analogy of probably safety requirements aboard the ISS.

5 Component Study

5.1 Component Selection

This study adopts the hemispherical PV diffuser presented by Georgescu et al. (2021) as its subject component. This geometry was selected in turn from the work of Bolashikov et al. (2014), which demonstrated that a six-lobed hemispherical nozzle, as shown in Figure 1, outperformed circular and elliptical diffusers in delivering clean air to the BZ at short distances. Further, Bennia et al. (2020) confirmed that the six-lobed configuration is superior to the five-lobed configuration, as the latter yielded worse spatial mixing, as demonstrated by their large-eddy simulation study of lobed and swirling HVAC jets.

In justifying this selection, it is necessary to critically compare it against the existing CQ diffuser across the key performance criteria established in Section 4. The existing louvred grille delivers broad, low direction bias airflow from a 1x4 array of louvred rectangular regions. It was designed to meet the ventilation specification as defined in the original 2008 installation. However, it is not designed to address localised CO₂

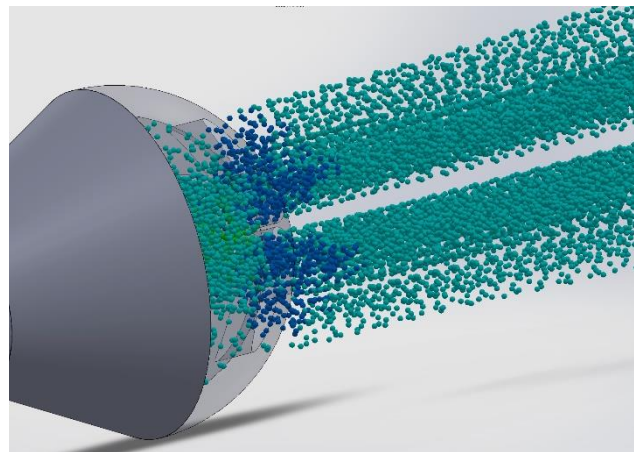


Figure 1, SolidWorks Flow Simulation of the six-lobed hemispherical PV diffuser nozzle. J Fernandes (2026)

accumulation in the BZ. Evaluated against the requirements of Section 4, the louvred grill underperforms on three of the four criteria: it cannot deliver targeted lateral airflow to the breathing zone, its geometry produces no meaningful TKE at face distance, and its adjustable louvre mechanism seems to provide no practical benefit to operation, as it was found to be routinely left in a fixed position by crew, as per Broyan and Cady (2010).

The six-lobed PV diffuser addresses all three inadequacies. The geometry, consisting of a hemispherical dome of equivalent diameter

$$De = 30mm$$

where De is the diameter of a circle whose area equals the combined area of all six lobe openings, useful as a consistent reference dimension for jet flow calculations. With six equally spaced lobed openings at 60° intervals, positioned laterally at $2De$ (60mm) from the astronaut's face, supplied with

1 m³/h of air, yielding an exit velocity of 0.4m/s. The supply tube bore is 24mm in diameter, giving an inlet velocity of 0.61m/s. Georgescu et al. (2021) validated this configuration experimentally using hot-sphere anemometry

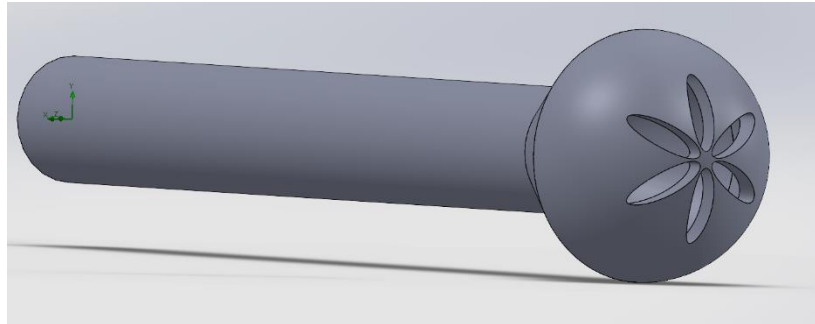


Figure 4, CAD model of the six-lobed hemispherical PV diffuser nozzle. J Fernandes (2026)

and CFD, confirming an 8% reduction in inhaled CO₂ per breath, relative to general ventilation baseline, with Draft Rates within EN ISO 7730 recommendations.

The selection is not without limitations, the 8% reduction in inhaled CO₂ is modest, and over the 60 second simulation window accumulations of CO₂ in the BZ continue to rise. The improved PV system reduces re-inhalation per breath but does not eliminate accumulation. At Re = 1200, the flow is in the laminar-transitional regime, which limits the TKE achievable through geometry alone regardless of nozzle design.

These limitations do not invalidate the component selection. No alternative PV geometry exhibits higher validated performance at this flow rate and standoff distance in current literature, but they contextualise the degree of improvement that AM manufacture of this component could be expected to deliver.

5.2 Why this Geometry Requires Additive Manufacturing

The six-lobed hemispherical PV diffuser could be manufactured by conventional polymer processing, specifically injection moulding. The argument for AM is one of practicality and economical superiority at the scale and volume relevant to this application, and the adjustability not otherwise possible.

The six-lobed hemisphere geometry presents challenges for injection moulding. The lobed undercuts on the dome face and the internal structure of the component, featuring a shrinking of diameter towards the shaft, would necessitate a complex mould, adding tooling complexity. Although not insurmountable, it carries a significant cost. A complex precision mould is estimated to be in the range of £30,000-60,000. There are four installed CQs aboard the ISS, ISS manifest strategy for non-critical replaceable components typically carries spares at 1:1 with installed units per annual resupply cycle. Further, NASA data indicates that approximately 95% of spare parts launched to the ISS remain unused (Prater et al., 2018). Considering this, it is likely that aside from the initial 8 units produced, only one replacement would be necessary per annual resupply. At this volume, tooling cost per unit

for the first year of production remain within the range of £3750-7500. More significantly, any changes to the geometry would require retooling of the moulds, potentially even a complete replacement. The economic case for conventional tooled manufacture at this volume is therefore weak, not due to manufacturing infeasibility, but return on investment for tooling.

AM features a few capabilities that lend themselves to this application. Firstly, no tooling is required, components can be manufactured to specific dimensions without reliance on casts or moulds. Second, AM allows the opportunity for crew and situation specific geometries. The existing louvred grille's adjustable mechanism was found to be routinely left in a fixed position, suggesting adjustability adds mechanical complexity without operational benefit. AM enables a different approach, rather than one adjustable nozzle, multiple geometrically distinct nozzles can be printed with exit angles optimised for the preferences and sleeping positions of individual astronauts. A geometry change that would require a new injection mould conventionally, is a minor CAD adjustment in AM, with no additional costs. This mass customisation capability is identified by Wiberg et al. (2023) as one of the core advantages of DfAM.

One manufacturing limitation must be acknowledged, FFF produces internal surface roughness with an approximate radius 10-20µm on channel walls, depending on print orientation and layer height. This is measurably rougher than an injection-moulded surface and raises questions on whether wall friction meaningfully degrades flow performance. The Darcy-Weisbach friction factor, from which friction-induced pressure drop is derived, takes the following form in laminar flow:

$$f = \frac{64}{Re}$$

Roughness only enters as a variable in the turbulent regime. The Reynolds number at the PV diffuser is approximately 1200, well within the laminar regime of <2300. The wall roughness of the lobe channels has no effect on friction factor or pressure drop under the operation conditions defined in Section 4.3. The dominant pressure losses are form losses at the lobe entry and exit geometry, no wall friction. The FFF surface roughness therefore does not meaningfully affect pressure drop through the nozzle. However, roughness may still influence the velocity profile of the jet exiting each lobe, by promoting earlier boundary layer development along the lobe walls. This secondary effect is acknowledged, but unable to be quantified within the scope of this study.

5.3 Design Failure Modes and Effects Analysis

A Design Failure Modes and Effects Analysis (DFMEA) was conducted to identify potential failure modes from the transition to AM manufacture in microgravity. The analysis focuses on failure modes specific to the FFF process, and the operational environment of the ISS, rather than the component's

ventilation function, as the functional performance of the geometry is validated by Georgescu et al. (2021). Key findings are summarised in Table 1.

Table 1, DFMEA for ISS CQ PV diffuser nozzle. J Fernandes (2026)

Failure Mode	Effect	S	Root Cause	O	D	RPN
Bore cracking or insufficient thread engagement during self-tapping installation	Nozzle not secured to duct fitting, potential detachment and airflow loss	7	Printed bore undersized/oversized	3	5	105
Lobe channel blockage by print artefacts	Reduced TKE, degraded carbon dioxide clearance	6	Insufficient print orientation, fine lobe geometry	3	4	72
Dimension error in lobe geometry	Jet misdirected, Performance deviations from CFD predictions	7	FFF tolerances on curved hemispherical surface	4	4	112
Material off-gassing in pressurised cabin	VOC exposure risk to crew	9	Incorrect filament / contaminated feedstock	2	3	54
Print failure mid-job	Partial part, Restart Required, Delay to repair	4	Power fluctuation/AMF data error	3	6	72

The highest risk failure mode is bore cracking or insufficient thread engagement during self-tapping installation (RPN 105). The printed borer diameter is critical. Too tight, and the metal duct cracks the bore on first insertion, too loose and the self-tapped thread has insufficient engagement to retain the nozzle. This risk intersects directly with the dimensional accuracy failure mode 9RPN 112), which makes it double consequential. Both are mitigated by the same measure, post-print dimensional verification of the bore diameter against specifications before installation. Airflow performance is additionally verified using an anemometer against the known 0.4m/s velocity target. The material off-gassing risk, whilst low in occurrence, carries the highest severity score and is managed through strict feedstock sourcing and traceability.

5.4 Potential for Geometric Improvement Through AM

A further benefit of AM manufacturing is that it opens the possibilities for geometric improvements that have no equivalent in conventional manufacturing. The lobed diffuser literature identifies several modifications with theoretical support for TKE generation. These include lobe deflection angles, tilting the lobe axis from the radial direction to strengthen streamwise counter-rotating vortex pairs (Nastase and Meslem, 2010). Scalloped inter-lobe valley edges that seed the shear layer with small horseshoe vortices (Yu et al., 1995), and sub-lobe chevron notches at lobe exits, which have been demonstrated to increase TKE by up to 65% (Callender et al., 2009).

With a 0.4mm diameter nozzle, all three enhancements are within the capabilities of FFF. AM enables these improvements to be prototyped, printed and evaluated with no additional cost or lead

time, a marked improvement on traditional design iteration. This represents perhaps the most valuable aspect of on-orbit AM for non-critical component development.

6 AM Process and Material Selection

6.1 AM Process

Two AM processes are currently available aboard the ISS, FFF via the AMF, and wire-arc Directed Energy Deposition (DED) metal printing. Selection requires evaluation against the requirements of Section 4, and the operational limitations of the environment.

FFF via the AMF has been operational since 2014 (NASA NRTS, 2014), it has produced over 200 parts and is a routine maintenance asset (ISS National Laboratory, 2025). Its power draw, operational overheads, and max envelope are all within the constraints of this component. Supported materials include ABS, HDPE, and PEI/PC, with a 152x152x152 mm build envelope.

The Metal 3D printer, whilst a landmark achievement, has severe limitations for this purpose. It uses a high-power laser in a hermetically sealed enclosure, requires remote monitoring during operation, and produces parts with no surface finish, and no capacity to apply them. The steep operational requirements, coupled with the inability to surface finish the part, and high cost of manufacture make it unviable for use in general component manufacture at this time.

6.2 Material Selection

Three filament types are approved for use in the AMF: ABS (acrylonitrile butadiene styrene), PEI/PC (polyetherimide/polycarbonate) and HDPE (high-density polyethylene) (Redwire Space, 2019). Selection between these requires evaluation against criteria most relevant to a life support airflow component in a pressurised habitable environment: flammability, mechanical performance, dimensional stability, and recyclability.

ABS is the AMF's most widely used material; it's low cost, high adoption and accurate dimensions. However, it does not meet FAR 25.853 aircraft interior flammability standards. In an enclosed pressurised environment, all byproducts of combustion are retained and potentially inhaled by crew. Mechanically, ABS offers a tensile strength of approximately 42 MPa, potentially adequate for this application, but with little confidence in its ability to withstand accidental loading or multiple installations and removals from the threaded metal pipe. ABS is recyclable on the ISS.

HDPE also does not meet FAR 25.853 standards. Mechanically, it has the lowest dimensional accuracy of the three.

PEI/PC, also known as ULTEM 9085, has seen limited use compared to ABS, and NASA publications on its ability to print fine features is not publicly available. However, it is theoretically dimensionally

stable, it is also recyclable, has a tensile strength of 71 MPa, almost double ABS', and crucially, it does meet the criteria for FAR 25.853.

The principal limitation of PEI/PC is that it is significantly more expensive than ABS, coupled with the lack of resources on its dimensional accuracy in microgravity, empirical validation would be required prior to operational deployment.

7 Critical Evaluation

7.1 Supply Chain and Logistics

The PV diffuser nozzle studied in this report is one component. The broader argument for on-orbit AM extends across a multitude of non-critical replaceable polymer components aboard the ISS. This broader argument is as compelling as the component case, understanding it requires examining the shift from physical to digital inventory, mass and volume savings on resupply missions, lead time elimination, and rapid iterative design capabilities.

7.1.1 Physical to Digital Inventory

The ISS spare parts model currently operates on a physical inventory ideology. Speaking strictly on non-critical components, spares must be present in a 1:1 ratio to the number of used components, and resupplies are scheduled once a year. As discussed previously, approximately 95% of spares aboard the ISS are never used (Prater et al., 2018), being there only as a mass redundancy. Further approximately 15% of ISS waste is thermoplastics (NASA, 2025), indicating they are used substantially aboard the ISS.

On-orbit AM flips the logic, a single spool of ULTEM 9085 filament, weighing 0.5kg, carries the potential to produce dozens of distinct components, saved as digital design files. Allowing for a complete replacement of the physical inventory of spare parts, or for true redundancy, a decrease of physical spare parts, for redundancy in case issues arise with AM maintenance. This represents a significant structural change in how spares could be managed.

7.1.2 Mass and Volume Savings on Resupply Missions

Current commercial launch providers, such as the Falcon Heavy, deliver cargo to the ISS at approximately \$1500 per kilogram (Jones, 2023). Every kilogram eliminated from the manifest carries meaningful financial value, or the capacity to manifest more parts not attainable through AM. Individual polymer components are lightweight, but their volume, packaging, and protective enclosures add overhead. A set of eight PV diffuser nozzles might represent 0.5-1kg of manifested mass, the equivalent feedstock to produce them in orbit is a fraction of that. Across dozens of polymer spare part lines, the aggregate mass and volume savings compound substantially.

Volume is an equally important constraint, pressurized cargo volume is limited and competed for by consumables, science payloads, and crew supplies. Pre-manifested spares that are never used occupy this volume for the duration of their journey, and ultimately, they are often disposed of. On-orbit AM eliminates the volume cost of unused spares, and with the potential for recyclability, reduces the burden on return vehicles carrying waste.

7.1.3 Lead Time Elimination

Conventionally, non-mission critical components are resupplied once a year, with lead times on procurement, manufacture, transportation to launch sites, it can feasibly extend this to 24 months. Should a component fail unexpectedly, crew must work around the limitations imposed by the failure or wait for the resupply mission to continue utilizing the component.

On-orbit AM reduces the supply chain to three steps, identifying the failure, transmitting design files from the ground, and printing a replacement. This timeline is measured in hours to days, rather than months.

7.1.4 Rapid Design Iteration

Perhaps one of the most significant benefits of on-orbit AM, the ability to iterate and improve designs whilst avoiding the costs associated with traditional manufacturing and supply chain conventions. On Earth, a design change to an existing spare part requires a new drawing release, new manufacturing, qualification testing, approval of manifest, and a 12–24-month delay before the improved part reaches orbit. For non-critical components, where the safety risk of the improvement is low, this process is disproportionately costly and complex.

With on-orbit AM, an improved design can be developed on Earth, validated through CFD and simulation, and transmitted as an updated design file to the AMF within days. The crew can print the new version and compare performance of the improved part within a single maintenance window. This mirrors the principle established by Wiberg et al. (2023) that DfAM enables not just better components, but a better design process.

7.2 Waste and Sustainability

AM is often characterized as a near zero material waste process, in relation to subtractive manufacturing. For non-structural polymer components of the kind studied here, the material efficiency argument is valid.

However, although the ReFabricator installed on the ISS can recycle waste filament into feedstock, this capability has only been demonstrated at a small scale. Further, terrestrial studies of recycled FFF feedstock indicate measurable degradation in tensile strength and dimensional consistency after repeated processing. If this applies to on-orbit recycled feedstock, components produced with the recycled feedstock may not meet the same tolerances as the original material. This is particularly relevant for objects with complex geometries, such as the PV diffuser discussed here. Further investigation into dimensional accuracy and structural integrity of recycled feedstock on-orbit is warranted before it is relied on for component production.

8 Conclusion

This report has presented a DfAM case study centred on the six-lobed hemispherical personalised ventilation diffuser nozzle for the ISS CQ, supported by peer-reviewed literature and well-documented performance limitations of the existing CQ ventilation system. The selected component, proposed by Georgescu et al. (2021), demonstrates a proven 8% reduction in inhaled CO₂ per breath, somewhat alleviating the microgravity breathing deadspace mechanism identified by Dutta et al. (2026).

The primary argument of this study is economic. At a realistic production volume of 8 units in the first year, and one per year following, the tooling cost of a conventional injection moulding renders it economically unfeasible, further reinforced by NASA data indicating 95% of spares are never installed (Prater et al., 2018). AM eliminates tooling entirely, reduces lead times from 18-24 months to hours-days, and enables design iteration at minimal cost. Secondly, the hemispherical lobed geometry presents injection moulding challenges that, while not impossible, add significant cost and complexity. Meaning AM is the ideal route to realising full performance potential for this component.

The AM process and material selection, FFF with ULTEM 9085, via the on-orbit AMF, has been justified against functional requirements and on-orbit manufacturing constraints. The metal AM capability was evaluated and found inappropriate for this application at its current technology readiness level.

The critical evaluation identifies substantial opportunities in supply chain simplification, mass reduction, and tooling cost elimination, all of which carry significant at approximately \$1500 per kilogram of orbital cargo. Process constraints related to FFF anisotropy, build envelope and surface finish quality have been acknowledged and addressed. More broadly, the case study demonstrates that components designed under the constraints of conventional manufacturing show promise in optimisation opportunities when re-evaluated through the lens of DfAM.

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