Formulating the 3D Printed Habitat Challenge

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This document summarizes how NASA's Centennial Challenges Program, along with NASA's additive construction subject matter experts and experts from outside the space industry, created and formulated the 3D Printed Habitat Challenge (3DPH). It highlights the important decisions that shaped the problem that participants would solve when they competed.

The challenge presented a series of relevant problems to a broad audience, with multi-million dollar prizes for the best solutions. Its aim was to incentivize non-traditional, (and even) non-aerospace entities to contribute to a NASA problem, in the hopes that their solutions would advance the state of the art of additive construction. By all accounts, both inside and outside NASA, the 3DPH challenge was a huge success. The challenge launched in 2015 and ended in 2020.

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1 Introduction

National Aeronautics and Space Administration (NASA) plans to land astronauts on Mars but faces steep mission costs to do so. Putting objects in orbit is expensive: one additional kilogram of launch mass adds thousands, if not millions, of dollars to the overall mission [3D180]. The astronaut crew will need thousands of kilograms of infrastructure and consumables to stay alive; this makes the cost problem many, many times worse [3D190]. To address this issue, subject matter experts (SMEs) across the agency investigate how resources on Mars could create the needed products instead of transporting them from Earth [3D180, 3D115, 3D191].

One such approach is additive construction using resources in-situ [3D65]. This construction method draws on additive manufacturing and uses a robotic printer to lay down successive strips of material. These strips fuse to form the desired object. Additive construction could reduce *both* the construction costs and risks. First, it uses materials found on the planet's surface to construct things like landing pads, roads, and even habitats [3D180, 3D130, 3D190, P23]. This way, NASA could avoid launching "thousands of tons" of construction material and save many millions of dollars [3D180, see also 3D190, 3D120]. Second, it reduces the risks of constructing the needed infrastructure. The crew will need adequate, large-scale housing for their monthslong stays on the planet. But, at current levels of shielding, the radiation levels on Mars make it extremely dangerous for the crew to construct this infrastructure when they arrive [3D226]. Instead, NASA envisions robots performing these tasks remotely, with a high degree of automation. Additionally, the independence promised by this technology will reduce the risks of accidents during the construction process [P23, 3D120, 3D190].

To help address this gap, NASA's NASA Centennial Challenges Program (CCP) launched a series of public-facing technology competitions to spur the development of these technologies. NASA's 3D Printed Habitat (3DPH) ran between 2015 and 2019, launching four prize competitions. I summarize the 3DPH Challenge below, focusing on the decisions that shaped the technology requirements participants faced. Specifically, how the 3DPH rules team decided what problems participants would solve.

This document proceeds as follows: First, I explain the origins of the 3DPH Challenge and the relevant context at NASA at the time. Then, I provide an overview of the 3DPH Challenge: its structure and timeline. Finally, I describe each competition: its aims, what participants would focus on, how the most important rules were decided, NASA SMEs' reflections on the outcomes, and any lessons that would carry forward.

2 A Challenge on Additive Construction

2.1 Why Launch a Challenge?

The push for a challenge stemmed from the Obama Administration—it would be a catalyst for technology development and nontraditional input. The Administration recognized additive manufacturing generally as a strategic priority for the US and wanted to encourage a broad exploration of this capability [3D1]. The administration also acknowledged that "knowledge is widely dispersed in society" and that innovation tools like challenges could tap into new and existing sources of expertise, benefiting the agency and the country [3D205, see also 3D206]. In this vein, it directed NASA and the U.S. Department of Energy (DOE) to spur innovation in robotics and additive manufacturing in 2013 [3D1, 3D30, P18]. Specifically, they directed NASA to draw on their prize authority[1] to spotlight specific research and development challenges that overlap with the agency's priorities [3D1].

NASA would decide what application of additive manufacturing they would challenge. NASA's CCP consulted with SMEs for input on applications of additive manufacturing that would make sense to space and non-space contexts [3D11, CCP7]. Here, CCP reached out broadly both inside and outside the agency. They approached contacts in industry (e.g.,

[1] In 2005, 51 U.S.C. §20144: Prize authority granted NASA legislative authority to use appropriated funds to conduct public prize competitions. NASA established the Centennial Challenges Program to award prizes for technical achievements that aligned with its aims.

Boeing and GE Aviation), government (e.g., United States Agency for International Development (USAID) and U.S. Army Corps of Engineers (USACE)), and additive manufacturing teams at NASA Marshall Space Flight Center (MSFC) and NASA Kennedy Space Center (KSC) [3D103, CCP7, 3D11]. In the end, the external input helped CCP settle on additive construction of planetary habitats [3D11].

The CCP reasoned that a challenge on additive construction in the space context would fulfill the administration's mandate: support ongoing work at NASA centers and attract the input of (non-space) non-traditional contributors. While planetary additive construction was a niche topic at NASA, it had the potential to make a big impact on long-duration surface exploration. By shining a light on it, CCP hoped that others would see this potential and help move its development along. Per the CCP Program Manager: "[the 3DPH Challenge] is the way that we, as an agency, reach out to all of you, our nation, to come and help us put a little piece of our puzzle in the journey to Mars" [3D122]. Additionally, building shelters quickly and efficiently was an area of active work in disaster relief and military contexts [3D11, 3D35, 3D33]. Much like printing infrastructure in space, these projects were concerned with minimizing the human effort required for the required structures and utilizing local resources and waste to the greatest extent possible. Being aware of the work of external teams on this topic, the challenge team hoped to draw these teams into the challenge as well.

2.2 Supporting Ongoing Work at NASA

2.2.1 Existing Additive Construction Programs at NASA

Research into additive construction for planetary surfaces had been ongoing at NASA. Specifically, teams at both NASA's Marshall Space Flight Center (MSFC) and NASA's Kennedy Space Center (KSC) pursued related technologies for several years [3D35, 3D160, 3D163]. These then collaborated on the Additive Construction with Mobile Emplacement (ACME) project, alongside several external partners like the USACE and Caterpillar [3D33, 3D34, 3D35]. The project brought space and non-space SMEs together to explore the overlap between printing temporary housing for the U.S. Army and the planetary infrastructure required by NASA [3D28], emphasizing developing the technology for large-scale printing [P17]. It also gave SMEs at KSC an opportunity to pursue the development of polymer concrete feedstocks[2]: these used plastics to bind, extrude, and layer regolith into the desired shapes[3D130]. In addition to having desirable material properties for applications in space (see 5.2.2 for a summary), they could also support sustainability efforts here on Earth [3D94, 3D185].

Notably, the ACME collaboration ran (almost) parallel with the 3DPH Challenge, with their expertise contributing to its formulation. The ACME project had only recently demonstrated large-scale 3D printing when the formulation of the 3DPH challenge started [3D65]. The ACME project and the 3DPH challenge had similar goals: large-scale automated printing of infrastructure with readily available materials [3D33]. Though they had not initiated the challenge, NASA SMEs on the ACME project knew that their expertise would, nevertheless, be required to formulate it [3D89, 3D11, 3D185]. They took this opportunity to shape the challenge towards their ends: once on the challenge's formulation team, these SMEs would ensure that it complemented their work. Below, an additive construction SME described how they saw the role of the 3DPH Challenge and CCP challenges more generally. Though Blake[3] joined the 3DPH Challenge's formulation team after it was already underway, they understood how closely related the challenge was to their work.

> Ademir: In your mind, where do challenges fit in [to your work]?
>
> Blake: A very complementary role to what we're doing. . . . In [the 3DPH Challenge's] case, it was so tightly interwoven with all the stuff we were doing in terms of the ACME system that we were building that there was no way that Finley[4] [an MSFC SME] and I weren't going to get pulled into the challenge. I was always monitoring it. [3D89]

[2] Analogous to a printer's ink.
[3] A pseudonym.
[4] A pseudonym.

2.2.2 Pushing solvers to explore useful solutions

The KSC and MSFC teams wanted to ensure that the challenge would extend their work. As such, these SMEs actively shaped the challenge to make it more likely that its outcomes would support their technical goals. First, based on their knowledge, SMEs would select technology areas that were particularly underdeveloped or highly uncertain and might benefit from external input. In particular, they would focus solvers on specific parts of the planetary additive construction problem, incorporating NASA's constraints and interests. Jude[5], an SME that assisted the formulation team, put it as follows: "we knew what troubles we were having, and we focused the competition to do something about those troubles" [3D185].

Second, SMEs worked hard to translate their knowledge of the Martian environment and NASA-specific interfaces into (reasonable) boundary conditions for the challenge. This way, the problems would—to a certain degree—reflect the conditions that they understood and were working towards. For example, Blake described how the SMEs wanted to impose their (current) knowledge on the challenge's rules. Specifically, what kinds of materials would be more favorable to create a feedstock for Mars: "We were getting our needs put into the system there. We were saying, 'we need to make sure that the materials [the solvers] use are as relevant to planetary materials as possible'" [3D89].

The SMEs' general approach to formulating the challenge was top-down. Having worked on this and related problems, SMEs were very familiar with the context. Their knowledge included the problem's important factors, for example, Mars' planetary conditions, materials available once the crew landed, current additive manufacturing capabilities, and more [3D36, 3D103, 3D80, 3D81]. To formulate the different phases and their competitions, SMEs would, first, think about the performance or development they wanted to incentivize. Then, they would figure out what assessments or evaluations were needed to ensure that solvers met that goal [3D93, 3D105]. SMEs "started at the macro and then went down more into the micro"

[5] A pseudonym.

in their formulation process, per Harper[6], one of the non-NASA members of the formulation team [3D105]. Harper went on by saying that at the "micro," the team would "[bring] reality in a little bit again" [3D105]. Specifically, questioning how non-NASA solvers could (realistically) meet the challenge, how they could practically score the incoming submissions, and what boundary conditions needed to be considered [3D105].

SMEs on the formulation team wanted to align the 3DPH problems to their internal ones *and* push solvers to explore new solutions. SMEs did not see themselves as (overly) prescribing what solutions to their problem would look like. Instead, they described how they were trying to balance a completely feasible problem and pushing the boundaries. As Ash[7], an SME on the formulation team, put it, "if it's completely feasible, then there's no point in having the competition" [3D103]. While SMEs understood key parts of the problem, there were many design decisions, trades, and practical issues to overcome [3D82, 3D89]. Here, solvers would explore that tradespace and develop solutions built on their expertise and knowledge. For example, Jude described how they viewed the balance between the leeway given to the solvers and boundaries on their solutions:

> [W]e didn't want to overconstrain the rules and prescribe a solution. We wanted to allow the teams to innovate and do things that we hadn't thought of. But we knew the basic building blocks that they needed to work within. We knew the basic constraints. . . . we knew we wanted to minimize launch mass, we wanted to use as much ISRU as possible, and we knew that there were things that we knew were getting close to be able to doing, but not quite able to do yet. So, we think they're possible, but we don't exactly know how to do it. So, let's choose things that they have to do, that are in that direction, so that we can actually learn from these guys too. [3D185]

2.2.3 Priority areas of additive construction

The SMEs ensured that this challenge would address key areas of additive construction. They focused heavily on developing new feedstock materials, ensuring the autonomous operation of the printer, and creating the robotic architecture required for large-scale structures [3D94, 3D11, 3D89]. The feedstock is foundational to this process: the printer prints with

[6] A pseudonym.
[7] A pseudonym.

in-situ materials, dictating its design and capabilities. Autonomous operations are required on Mars to protect astronauts from dangers associated with construction—ideally, the habitats will be complete before they arrive. Lastly, habitats are only useful for the crew when printed to scale—SMEs wanted printer systems to be designed and built with this in mind.

To make progress on the capability of additive construction, one would have to consider these priorities together. Per Ash, design decisions in one area impact the others: "It's a Venn diagram. They're all equally important, they all have their own challenges. They're all enabling. If you're missing any one of those— It's a three-legged stool" [3D94].

This interdependence increases the complexity of the challenge. Specifically, the printing system also limits what kinds of geometry—and thus types of infrastructure—can be printed. Blake stated this succinctly: "You can't build a printer that's open-ended and can build any geometry" [3D89, see also 3D226]. As such, the habitat design would have to incorporate all three areas to reasonably model a deployment to Mars. So, the architectural habitat designs and printing system designs became an additional focus area in this challenge[8] [3D11].

2.3 Drawing External Contributors

The 3DPH Challenge connected NASA SMEs with a range of people and organizations, both inside and outside the space industry. These contributed to formulating and solving the problem. CCP's long history of running challenges, with several high-profile successes, meant this approach was a known way to involve non-traditional entities [P13]. SMEs relished the idea of working with smaller, non-traditional players in their day job. They were, for example, "so much more nimble and flexible and can just change on a dime," compared to the larger aerospace multinationals that they would normally do business with [3D185]. Despite lacking resources, those entities "have great intellectual capital and have great ambitions," as Jude described [3D185]. SMEs appreciated that challenges would provide a (new) avenue

[8] There were other reasons for pursuing an architectural focus area, and these are explained in 4.1 and 6.3.1.

for external collaboration. Quinn[9], an SME on the formulation team, summarized how they saw the utility of challenges in enabling their work:

> [Challenges] have been good at finding innovation in unexpected places. Not necessarily government research institutions or academia, but really represent a great way to bring in garage maker innovators, who probably aren't out there applying for government contracts or even thinking about government work in any capacity. So, it's really an opportunity to bring them into NASA, you know, and let them help us with technology development. I think that's a really unique feature of CCP, that it's really that public-facing opportunity in a way that our traditional contractual mechanisms aren't sometimes. [3D36]

Entities outside of NASA, and even outside the space industry, contributed significantly to the problem NASA was facing. All competitions saw a mix of academics, companies, and hobbyists participate. In fact, SMEs were very open to input from different industries–they wagered that they would have different competencies and ideas relevant to the problem [P13, 3D104]. And they expected the challenge to facilitate that. As Ash described, the 3DPH Challenge team wrote the rules to overlap terrestrial and space industries, so "the competitors could still compete and meet their own goals while meeting NASA's goals" [3D103]. Fran[10], an SME who observed the 3DPH Challenge, described how they believed challenges could provide that avenue to connect with entities outside the space industry:

> We [at NASA] fight constantly to get outside the known group of people and companies that we deal with. How do we get outside the aerospace industry? How do we get the Bechtels, and the Caterpillars, and the mining companies involved when they don't go to the conferences we go to? They don't necessarily look at the government solicitations that are put out that we put out. A challenge breaks that paradigm somewhat. [3D100]

While non-space entities participated as solvers, some also contributed to the formulation of the challenge. The 3DPH Challenge team recruited external (non-space) advisors on the formulation team. This was a big deal for the challenge. Across all phases, they received input—or sponsorship—from SMEs in non-space industries, including international development, architecture, construction, and the military [3D105, 3D107, 3D108, 3D122,

[9] A pseudonym.
[10] A pseudonym.

CCP49]. These external SMEs would describe the capabilities of their industries to their NASA counterparts—what the state of the art and the barriers to entry were—and helped write the rules along these lines. It also became an opportunity to (re)connect or expand their connections to public or private sector organizations and use their knowledge [3D31, 3D94, LE1, LE3, P19]. Finally, the external SMEs also helped market the challenge to their own external communities, judge the solutions, and importantly, write the rules. One of the contributors, Caterpillar, even provided access to a facility to host the challenge's finals and equipment to test solvers' solutions.

Of course, solvers would also benefit from their participation in the challenge. Winning the large monetary prize was an important draw for many participants, but not the only one. Several teams wanted to use the challenge develop—and demonstrate—a technology, or to build a revenue stream in their company [3D196, 3D202, 3D210]. Others wanted to use the challenge to make a name for themselves through the challenge's visibility [3D198, 3D207]. Relatedly, challenge organizers would not only provide access to the (NASA and non-NASA) SMEs on additive construction, they would also introduce teams to potential sources of funding and even other competitors in the challenge [3D227].

3 The Structure of the 3DPH Challenge

The 3DPH Challenge would offer upwards of $2.5M to address the additive construction technology gaps it highlighted. Solvers would address these gaps–and win parts of this pot–across different phases of the challenge.

Across three phases, the 3DPH Challenge held four independent competitions: the Design Competition, the Structural Member Competition, the Virtual Construction Competition, and the Construction Competition. Each competition focused on different technical areas of interest to the NASA SMEs, with their own cohesive rule set, prizes, and judges [3D17, 3D31, 3D23, 3D76, 3D108]. Each competition also included (one or more) levels—nine in total. And each level had various performance goals, and the challenge team awarded a prize for the best performance(s). fig. 1 illustrates this structure below: each phase is pictured in light grey, their respective competitions in dark grey, and in turn, the different levels per competition are in black.

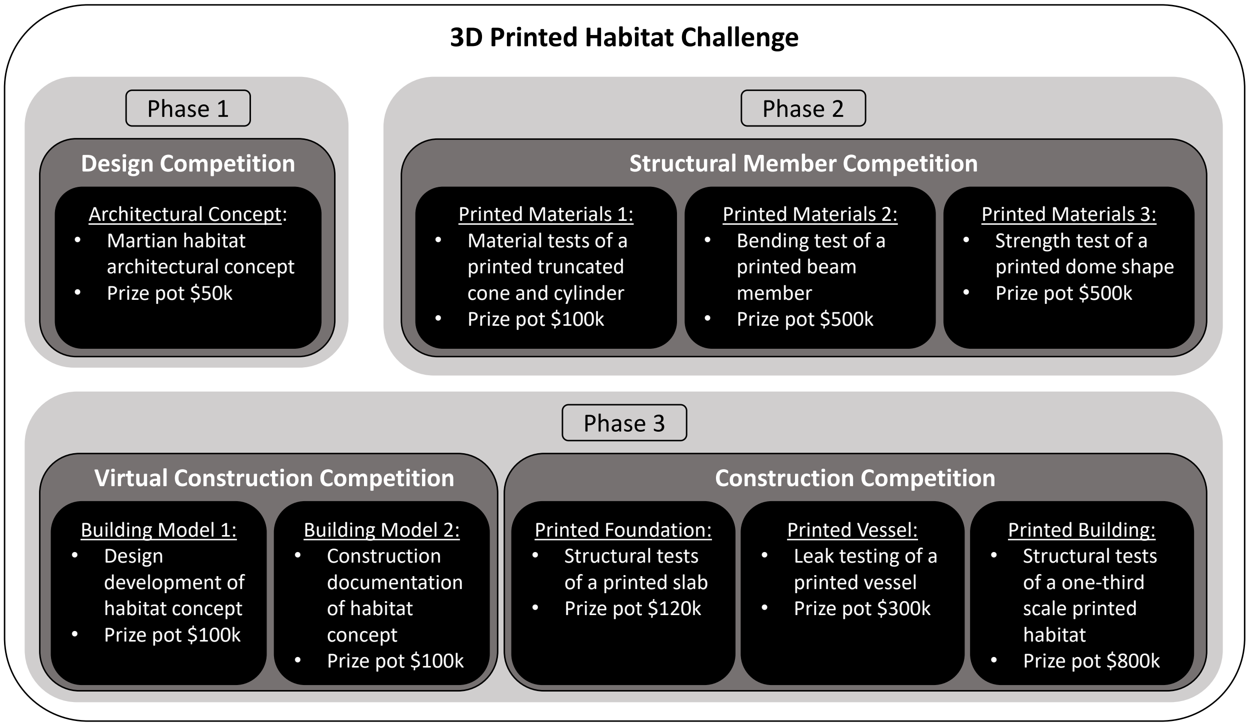

Figure 1: 3DPH Challenge Structure

SMEs did not decide the challenge's exact structure when they first conceived the 3DPH Challenge. Early on, the formulation team only had a high-level picture of what the challenge would look like: NASA's technology gaps and potential challenge goals. The team also believed that the challenge's phases "should gain in difficulty," serving an onramp for participants that had not already been working in the space industry [3D227]. Further details would solidify as the challenge progressed [3D103], resulting in the above phases. SMEs used this flexibility to learn from preceding phases and course-correct the challenge (and the rules) when necessary. fig. 2 summarizes when the formulation took place. It also emphasizes that formulation occurred across the challenge, with one major revision of the focus of the competition. As Ash described:

> Each time we started a new phase, there was a big debate on what should the new phase be. The phases were not really defined all the way in advance. . . . It's probably good that we didn't try to do the rules for Phase 3 before learning the lessons in Phase 1 and 2. So, [for] each phase, it's important not to get ahead of yourself. [3D103]

The sections below explain the evolution of the challenge's structure, focusing on how the challenge team formulated each competition.

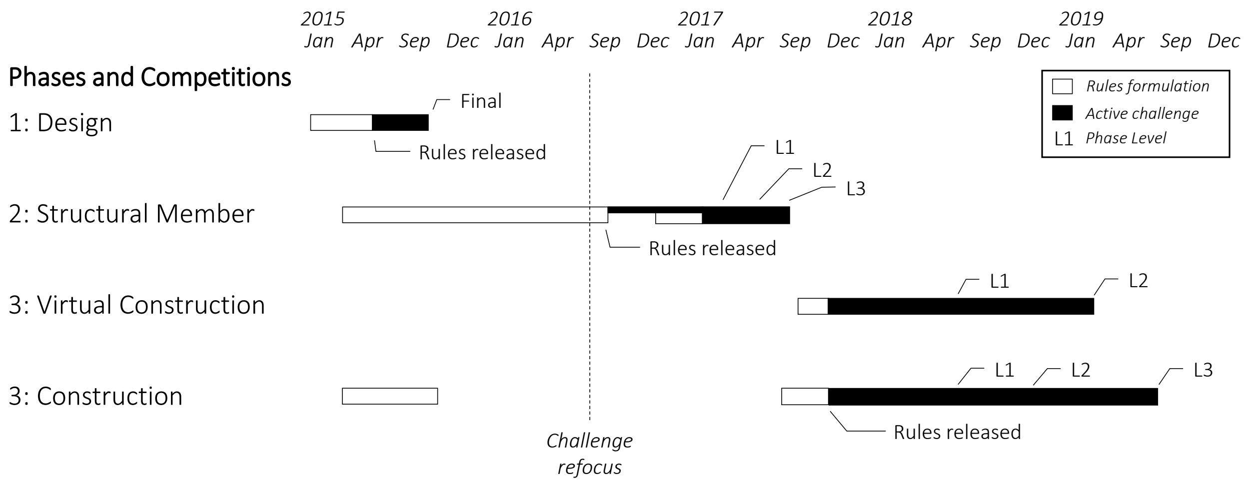

Figure 2: Timeline of the 3DPH Challenge

4 Phase 1: The Design Competition

The 3DPH Challenge's first phase consisted of the Design Competition. It challenged solvers to create architectural concepts for habitats on Mars. It was the shortest of all competitions, running from March 2015 to September of the same year. The Design Competition offered only one prize award, with a total prize pot of $50k. See fig. 3 below for a visual summary.

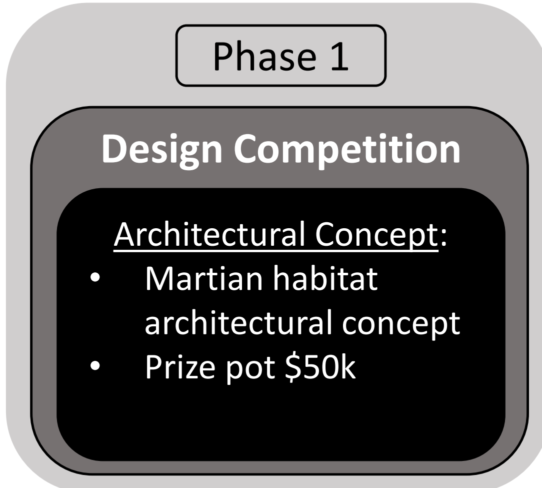

Figure 3: Summary of Phase 1 of the 3DPH Challenge

4.1 Establishing the Design Competition

4.1.1 The Focus of Phase 1

Additive construction is a new construction method, and its capabilities have barely been explored [3D3]. Like additive manufacturing, it lays down individual layers of material that combine to form a single solid shape. This method can enable several advantages over others, for example, automated and remote construction, quick and efficient building, and designs of structures and buildings that have either not been possible before or were more difficult to accomplish through other means [3D13, 3D65, 3D180].

In this vein, the Design Competition intended to explore the range of habitat designs that would be possible using additive construction [3D2, 3D17, 3D31, 3D69, 3D72]. The printer's design significantly influences what geometries it can print [3D160]; to obtain the widest range of designs, one would need to (allow others to) explore both simultaneously. The formulation team wanted to encourage the exploration of both, resulting in habitat designs that would suit NASA's aims for a Mars settlement [3D4, 3D117]—nominally, a structure to house four astronauts for one year [3D17]. Speaking to potential participants at Maker Faire 2015, the CCP Program Manager at the time described what kinds of solutions they wanted to see:

> I want you to think, "how can I use 3D printing, so I don't print a cube house with a slanted roof?" There's got to be more unique opportunities and more unique designs that can be taken advantage of because of doing 3D printing. [3D118]

4.1.2 Logistical considerations

The Design Competition, at least partially, served as a stop-gap for NASA SMEs to plan the subsequent challenge phases. During the early challenge formulation meetings, the team realized that they needed more time to craft good rules—especially for phases where they would ask solvers to demonstrate their solutions [3D30, 10CCP, 15CCP]. Specifically, SMEs wanted to dig into both the "material that would be used" and "the system to build the habitat," per Riley[11], a CCP team member that contributed to the early formulation of the 3DPH Challenge [3D11]. But the team was also under pressure to release something soon: there had been little progress on the Obama Administration initiative that had driven the formation of the challenge. Needing a quick win, the team figured that a design challenge could give them the delay they needed [3D11, 3D30]. So, the formulation team decided to get the approval for—and launch—the Design Challenge first[12] and return to the drawing board for the subsequent, bigger phases [15CCP].

4.2 Formulating the Design Competition's Problem

The formulation team drew heavily on the architecture domain because of the challenge's focus on building design. Here, they relied on the architectural experience of some of its members to shape the rules [3D4, 3D7, 3D8], and later, on architects to judge the competition [3D72, 3D80]. Ash summarized the formulation process for the Design Challenge as follows:

> In Phase 1, the goal was architectural design. So, we had architects on the team, and we asked them, "in your profession, what do you desire?" And if you go to the rules for Phase 1, you'll see the list of architectural criteria. And the rules were basically structured around those criteria. [3D103]

[11] A pseudonym.

[12] The 3DPH Challenge partnered with America Makes to provide logistical support in administering this competition [3D72, P5, P19, 17CCP].

These criteria shaped both the form of their solutions and the problem that participants would solve [3D3, 3D4]. For the former, the challenge would require a conceptual design (in documents and presentations) and its tabletop model—common deliverables for architecture competitions. By selecting these, the formulation team also tried to keep the costs of participating low[13], with early notes stating an estimated expenditure of no more than $10k [3D3]. Solvers would first submit their concept illustrations and descriptions for initial judging. If successful in these early rounds, the challenge would invite solvers to 3D print a small mockup of their habitat. As assessed by the CCP Program Manager when the challenge was launched: "What I see here is the combination of a paper project built into something that when people walk by, they can actually visualize what a habitat– What a house on Mars might look like" [3D119]. These deliverables resulted in what some SMEs called a "purely an architecture study" [3D100, see also 3D96].

For the latter, the highest-scoring areas would be architectural criteria. The formulation team grounded the judging criteria for the Design Competition in the tenets of architectural theory: "firmness, commodity, and delight" [3D7, see also 3D3, 3D8, 2018-05-31]. As such, while the criteria covered a wide range of areas for scoring points, the most important ones covered the novelty of the habitat's conceptual design (or aesthetics) and the design's application of additive construction. Per the rules: "Architectural concept and design approach, Architectural implementation and innovation, and 3-D Print Constructability will have HIGH weight factors" [3D17].

This architectural flavor, combined with the time needed to shape the other technical areas of the challenge, also affected other rules. First and foremost, the materials that the printers would use. This challenge extended the time available to SMEs for creating the rules governing the materials in the wider 3DPH Challenge. As such, the Design Challenge did not place a strong focus on what materials solvers would print with, despite its importance

[13] Note that some 3DPH teams invested upwards of $800k to participate in Centennial Challenges [3D98]; I use "low" relative to these investments.

to the system's design[14]. While the rules heavily emphasized NASA's intent to use "mission recycled materials and/or indigenous regolith materials" [3D17, see also 3D13], they did not specify these materials besides stating "in-situ resources" [3D17]. SMEs like Ash, for example, did not think materials were important in this phase: "It was an architectural design, so the materials didn't matter in Phase 1" [3D103].

Second, and in the same vein, the rules gave solvers a lot of freedom in their designs. There were very few rules to constrain the designs to what the SMEs would deem appropriate [2017-07-27]. Notably, the rules prescribed a minimum habitable area of 1000 ft^2. Per Quinn, this number was likely derived from existing NASA studies on human area and volume requirements for specific tasks [3D226, see also 3D17, 3D76]. Additionally, all solutions must allow for "a minimum of three 45 ft^3 (1.3 m^3) spaces" to contain life support equipment for the four astronauts [3D17, see also 2017-07-27, 3D10]. Additionally, with reference materials provided as a guide [3D97], all solutions must also pick the site where their habitat would, ideally, be located [3D17].

However, other Mars-focused rules were optional. Even with the requirement for selecting a habitat location, solvers did not have to tailor their design to the Martian surface [3D17]. Though earlier versions of the rules did require this [3D2, 3D7], the final version asked for an analog habitat structure[15] located on Earth: a "prototype for the one that they'll reside in while on Mars" [3D10, 3D17]. As such, SMEs did not require solvers to take Martian surface conditions (e.g., vacuum, radiation, temperature, etc.) into account. Additionally, while solvers needed to specify their HVAC and power outlets, detailed electrical, plumbing, and ducting plans were "not required" per the rules [3D17].

[14] Early drafts of the Design Challenge rules included limits on what kinds of material were fair game for solvers: they stated that solvers would design "using only indigenous materials or with recyclable materials additives" [3D10, see also 3D7, 3D8, 3D9] or even "just plastics" [3D6]. But these constraints were later removed.

[15] After the 3DPH Challenge, NASA NASA Johnson Space Center (JSC) would contract with a 3DPH competitor to design and print such a structure [3D184]; see 6.3.4. Nevertheless, this design did not direct solvers to address NASA's aims for Martian systems.

4.3 Outcomes of the Design Competition

Interviewees differed on the merits of the Design Competition. The CCP touted the strong response and varied out-of-discipline participants; here, it awarded a total of $40k to the winners, with first-place taking home $25k. The winner even collaborated with a NASA team after the competition. However, SMEs on the formulation team (and those involved in later 3DPH phases) were generally skeptical of the solutions submitted. I elaborate below.

4.3.1 Reflections on Participation

The Design Competition succeeded in reaching out to non-traditional individuals and organizations. In total, the challenge received close to 165 unique entries[16] [3D72, 3D127, CCP144, P5], with 30 selected to participate in the final round [3D72, 3D127]. These participation levels were unheard of for the CCP's challenges. Per one of the CCP team members, this "[was] unprecedented. [The challenge] worked masterfully for that purpose" [P19]. The solvers—participating as individuals or teams—ran the gamut of hobbyists/independent innovators, start-ups, academic groups, large businesses, and even other space agencies [3D31, 3D127, 3D194]. And while many had a strong background in the space industry, most (finalists) came from the architecture, 3D printing, and design industries [3D26]. In short, SMEs like Fran thought the challenge succeeded in "[getting] a whole bunch of people involved" [3D100].

Additionally, the challenge attracted teams outside of the space industry that wanted to collaborate with NASA in some capacity. In my interviews, two teams participated in the Design Competition to establish a relationship with NASA SMEs, hoping to pursue future contracts to apply their expertise [3D195, 3D196]. Others likely had the same inclination as well. For example, when I asked one participant—an architect—what types of prizes would have also attracted him to the Design Challenge, his response was: "A real contract or a

[16] Available documentation differs in how many teams participated: CCP summary documents describe 162 [3D72], 165 [3D99, 3D127, 3D109], or 167 [P5]; CCP leadership recollections note 164 [P19].

job with NASA" [3D88]. In short, their participation in the challenge might have been the beginning of their involvement in the space industry.

4.3.2 Reflections on Solutions

Teams geared their designs towards the Martian surface, NASA's real aim, despite its optional requirement in the rules. For example, the top 30 finalists—several times the average number of finalists for Centennial Challenges [P5]—all designed their habitats (and associated printers) with NASA's application in mind and not the training facility described in the rules [3D26]. Several solvers were delighted at the chance to apply their architectural skills to a design problem they had never encountered before. Solvers I interviewed described how the challenge brought their aerospace and architecture interests together in one challenge [3D197, 3D198, 3D207]. They took NASA's aims to heart and intended to "come up with a very rational, very hardheaded solution to this problem" of designing habitation systems for Mars [3D196]. To help them in their designs, (some) teams reached out to experts on the Mars environment on an ad-hoc basis [3D156, see also 3D188, 3D195, 3D196].

There was an expectation that participants would bring in state-of-the-art ideas. They would not be burdened by the ways that NASA usually does things. Instead, as one CCP team member described, participants were free to be creative "because they don't have the thinking constraints that we have. I think that alone is very valuable" [3D104, see also 3D187]. The formulation team made this expectation clear in the rules [3D12, 3D13, 3D17] and the marketing material [3D117, 3D118].

By all accounts, solvers' designs were second to none for communicating NASA's aims for long-duration stays on Mars. Per the SMEs and CCP team members, these showed the public NASA's intent in ways that were more compelling than NASA could achieve [3D71, 3D119]: solvers envisioned structures on Mars where people could live, instead of just surviving in a module [3D187]. Both the formulation team and NASA personnel who observed the challenge regarded the designs—and their associated media products—as nothing short of "beautiful"

[3D160, 3D193, 3D187]. A CCP team member concisely summed up the achievement of Phase 1 as follows:

> [The solutions] provided a way for the general public to visualize the designs, the final products, in beautiful concepts that helped NASA communicate what we needed to out of discipline potential participants. This stage helped bring to the public conversation a very complicated subject. [3D193]

However, the challenge's lack of technical requirements in the rules, or judges to vet the solutions, left the relevant SMEs skeptical about the feasibility of the solutions. Simply put, the beauty of the designs and the quality of their media products did not convince the SMEs of the technical value of the solutions. Because of the architectural focus of the challenge, SMEs questioned the fidelity of the solutions. SMEs—both NASA and non-NASA—described this phase as "more kind of a concept" [3D80], where solvers could "make up something that could be a habitat on Mars, and draw a picture of it" [3D88, see also P18, 3D122]. They questioned the methods solvers used in their habitat analyses [3D106]. Referring to the delay in placing rules on the materials used to print, they emphasized how "what [the habitat] looks like is not as important as what it's made of" [3D122].

The skepticism of the solutions stemmed from mismatched expectations of solution content. Specifically, those involved with infusing the architectural focus into the challenge were looking for fundamentally different things than the additive construction SMEs. Here, Quinn described "some tension there between the competition that is focused on architectural concepts and the space exploration people who come at it from different perspectives" [3D80]. As a result, while allowing a lot of leeway for "dreamers," this phase lacked the guide rails to ensure the solutions were rigorous in the eyes of SMEs [3D226].

The lack of (required) details in the solutions, in turn, cast doubt on their potential feasibility. SMEs were much more concerned, especially at this stage, about coming up with designs that would work. Blake, for example, thought: "I don't really care what it looks like, but I want to make sure it doesn't kill me" [3D160]. But the judging criteria and judge's assessments did not elicit, or rank, solutions according to how well they kept astronauts alive

[P19]. Along these lines, Quinn recalled asking a fellow formulation team member for their thoughts on the solutions:

I remember [one SME] talking about the architects, being like, "Oh, this has a high level of— It's very aesthetically pleasing." [This SME] comes at that from a completely different angle. [In their mind,] yeah, this concept art looks pretty, but you couldn't actually ever, ever build this thing. [3D80]

Moreover, seeing these solutions and the skills these teams brought to bear convinced the SMEs that they needed to reach out to different communities for the subsequent phases [3D94].

4.3.3 Partnerships Resulting from the Design Competition

One team collaborated with NASA directly after the Design Challenge. The winner—SEARCH+, a team of architecture graduates and practitioners—collaborated with a group at NASA Langley Research Center (LaRC) [3D166, P18]. The LaRC team pursued habitat concepts that used water ice as a construction material [3D171], and it coincided with what the winner used in their design [3D165]. This overlap encouraged the LaRC Team to reach out to the 3DPH team [3D125, P19]. The two would collaborate on a design charrette to revise LaRC's original concept to a habitat [3D38, 3D39]. Here, the LaRC team relied on the 3DPH team's architecture, "graphical art, and human factors" experience to inform the design [3D125, see also 3D37, 3D124, 3D164, 3D165]. The value of this collaboration was approximately $20k [3D212]. Note here that the LaRC team was not involved with the formulation of the 3DPH Challenge [3D125]. And while their designs both used water ice found on Mars, LaRC's design did not rely on additive construction [3D38, 3D39, 3D156].

5 Phase 2: The Structural Member Competition

The second phase of the 3DPH Challenge contained the Structural Member Competition. It challenged solvers to (create a system to) print standardized material test items from likely Mars ISRU materials. This competition consisted of three levels, requiring different and more complex objects. Accordingly, the prize pots for these levels were \$100k, \$500k, and \$500k, respectively. While the Structural Member Competition's formulation started in 2015, it did not open until late 2016—it, along with the challenge, underwent a major redirection and reformulation during that time. It held its final level, the head-to-head, in late 2017. See Figure 4 below for a visual summary.

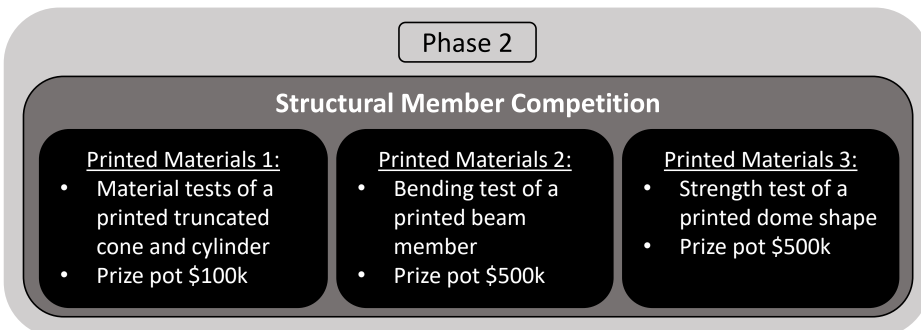

Figure 4: Summary of Phase 2 of the 3DPH Challenge

5.1 Establishing the Structural Member Competition

5.1.1 The Focus of Phase 2

Of the technical areas related to additive construction on other planets, what materials would be used as feedstock was the most crucial. It was where the rubber met the road: any mass (and cost) savings of importing materials would depend on how much raw material could be converted to usable construction material. As such, the thrust of this area would be to design and test ways to turn materials available on Mars into a printer feedstock suitable for creating the infrastructure that astronauts need. As Riley described, the Structural Member challenge would "focus on the material that would be used" [3D11]: solvers would "develop a good material" by coming up with a "recipe" suited for NASA's aims, as well as test its physical properties once printed [3D11, 167CCP, 3D103].

Most of the technical uncertainty of the printing system resided with feedstock composition as well. SMEs described the low TRL level of suitable materials relative to the other technical areas [3D95, 3D103]. While NASA SMEs had worked on a range of potential feedstocks separate from the 3DPH Challenge [3D101, 3D130, 3D180], they recognized that many different combinations of materials (with varying mechanisms of printing) would be possible, each presenting different material characteristics [3D122]. The NASA team had not, and likely would not be able to, span the whole space of options. Simply put, materials development was important but difficult, requiring a lot of effort to produce a printable substance [3D101, 3D102]. As Quinn described:

> Something that I always thought was so difficult in this [3DPH Challenge] was the materials development aspect of this. I always thought this could be an entire challenge in itself. Completely independent of the printing and the manufacturing system. Just developing the materials ... that is an immense challenge [3D101]

Formulating rules for a competition on materials proved to be difficult as well. What feedstock the printer would use had been part of the earliest discussions on what the 3DPH Challenge would address [3D11, 3D21]. However, formulating a rule set that balanced NASA's needs while still allowing participants to show novel solutions proved difficult, as mentioned in 4.1.2. The Design Competition gave SMEs the time and lessons they needed to structure this competition. In the end, the Structural Member Competition would incentivize solvers to design and demonstrate the basic technologies of printing something on the surface of Mars. Per a formulation team member, solvers would "come up with a, quote, concrete, and you can debate what that term means, to be made out of material that you can find on Mars and ... print with that material in a rather complicated shape" [3D88]. In short, develop the feedstock material and, in parallel, develop a robotic system that could deposit this material in prespecified shapes [3D69].

5.1.2 Refocusing the 3DPH Challenge in Phase 2

SMEs wanted to target a different audience for this phase based on the participation in the Design Competition. The previous phase successfully tapped into the 3D printer hobbyists, architects, and designers. But despite the enthusiasm and work solvers displayed in the first phase, SMEs did not think that these kinds of solvers possessed the skills to address NASA's technical uncertainties. Namely, while their design and 3D printing skills were relevant to the technology, SMEs estimated that these communities lacked the material development and robotics skills needed to create large-scale printing systems. Instead, they estimated that the relevant skills would reside (broadly) in the construction industry, likely due to their cooperation with USACE and the ACME project. Ash described their thinking at the time as follows:

> ... quickly we realized that [the maker community in Phase 1] was not the right kind of crowd because they were involved with small-scale 3D printing, and what we were doing was large-scale 3D printing, which is a whole different thing. It's more involved with the construction industry, with civil engineering and construction. After Phase 1, we realized that, and we revectored the whole competition. To a new target audience. [3D94]

The construction industry pivot impacted who solved *and* who formulated this competition. To get help doing both of those things, members of the challenge team started reaching out to potentially interested entities, both inside and outside NASA [3D27, 3D105, 3D121]. They reached out to members of the ACME project, who—in turn—connected the challenge to their project partners. SMEs also showcased the challenge at public events to spark interest in the challenge. These efforts were successful and managed to form crucial partnerships for the challenge [CCP71]. Here, Ash described the importance of partnerships outside NASA: "... and that's how we got it all going again. We got Bechtel onboard. We got Caterpillar onboard, VC– So that's how we got it going, by reaching out to external industry and not the space industry" [3D94].

For the subsequent phases, the 3DPH Challenge partnered with six external organizations. These were Bradley University, Caterpillar, Bechtel, Brick and Mortar Ventures, the

American Concrete Institute, and the United States Army Corps of Engineers (USACE) Engineer Research and Development Center [3D31, 3D189]. These were no strangers to additive construction technology: some of them had already collaborated with NASA on previous projects [3D27], but most had been following these technologies for several years [3D147, 3D150]. These partners supported the competition's administration, provided monetary and in-kind sponsorship, and assigned a number of their experts to help formulate the rules [3D108].

5.2 Formulating the Structural Member Competition's Problem(s)

5.2.1 Deliverables

This competition's focus was developing new feedstock materials, whose performance depends on the material's characteristics and the print process. Additive construction, like additive manufacturing, is an area where one cannot determine a material's characteristics separate from how the test sample was made. Different combinations of materials will produce feedstocks with varying properties. The material's bulk properties–like compression or tensile strength–are measured via an object created in layers of that feedstock. As a result, even high-performing materials can result in low-performing objects if the print process is lacking. For example, waiting too long to lay down a fresh bead of (cement) feedstock on top of a previous layer will impede their adhesion [3D89]. Then, the printed object might behave like two objects instead of one.

NASA SMEs, and likely others in the additive construction industry, create models to describe these interactions. But, at least at NASA, these are specific to Portland cement feedstocks—a common construction material [3D89]. These relationships, and the models that build on them, might change with different materials, print processes, or object shapes [3D89]. Blake, as an additive construction SME, described how uncertainty is introduced by a different printing process even when the material is the same:

> If you have a very well-defined bead and you put another very well-defined bead on top you know exactly what your bonding surface is, and you can calculate strength. A lot of times [additive construction companies] print straight down, so the bead squishes out and the bead contact surface area changes constantly. You can estimate an average, but you really don't know. [3D89]

Solvers demonstrating their feedstocks via printing was crucial for verifying the materials' performance. NASA and non-NASA SMEs hoped that these tests would "help us get to a base understanding of the materials themselves" [3D87]. None of these exceeded an area of 1 m^2—these were desktop-scale objects. Solvers would also provide documentation related to their feedstock designs.

5.2.2 Feedstock Composition

In contrast to Phase 1's open approach to feedstock material options, Phase 2 focused heavily on polymers. In fact, the earliest drafts of the Structural Member competition rules imagined solvers would focus exclusively; this idea persisted at least up to the launch of the Design Challenge [3D6, 3D11,3D118]. This focus stemmed from the NASA SMEs' contextual knowledge and their work on feedstock suitable for planetary surfaces. Specifically, SMEs at KSC believed that (various) polymers would be particularly effective as a material to bind the regolith material aggregate available on the surface [3D103, 3D137]. When heated, polymer flows like a viscous liquid, allowing the printer to deposit it and the regolith aggregate in layers. Per the SMEs, several factors weigh in this feedstock's favor compared to other types of material: a polymer feedstock requires a relatively low amount of power to heat it to a printable state; its print process is more easily controlled compared to other additive construction methods; it uses no water—a precious resource on Mars; it does not suffer from boil off in vacuum conditions; it offers some radiation protection; and, it is available immediately after landing (in the form of packing materials) or can be manufactured using in-situ materials [3D11, 3D25, 3D92, 3D94, 3D103, 3D137, 3D185, 3D227]. Additionally, the KSC SMEs were developing a polymer feedstock and its printer as part of the ACME project; they successfully demonstrated their printing system while Phase 2 was being formulated [3D130, 3D181]. As such, SMEs heavily preferred polymers due to their estimated performance combined with their in-house experience with this kind of feedstock. One SME on the formulation team described how this preference influenced how they wrote the rules:

> In Phase 2, we pushed hard on using polymers because it was feasible. It was a feasible solution that was really quite good. And I saw that from the work in [the lab], so [we] pushed on that pretty hard[17]

The SMEs' push for polymer-based solutions resulted in the rules favoring those designs. Though later iterations of the rules would broaden the material options for solvers, SMEs would still consider (further) demonstrating the feasibility of polymers as "one of the goals of the competition" [3D94, see also 3D6]. Specifically, the preference influenced the scoring weights for the choice of (constituent) feedstock materials and the proportion of their mass (mass ratio). I explain these below.

Feedstock materials SMEs' material preferences drove the rules on the feasibility of feedstock materials. In general, the SMEs wanted solvers to explore potential materials and their different forms for printing [3D122]. As Quinn stated about participating in the Structural Member Competition: "you actually had to do materials development as part of that challenge" [3D80]. To define and bound what solvers would explore for this competition, the formulation team enlisted the help of NASA SMEs—experts in Martian geology and polymers for space missions [3D11, 3D24, 3D36]. These focused on what would be available to the crew and their printing systems once they landed.

Here, several knowledge areas intersect and produce a large materials tradespace. First, Martian geology: Mars has an abundance of rocks, sand, and sediment types; water can be accessed in the form of ice or brines [3D11, 3D24, 3D102, 3D122]. Second, waste or excess materials upon launch: a slew of launch packing materials can be recycled into usable polymers [3D25, 3D80, 3D11, 3D122]. Lastly, additives that (for now) must be brought from earth to create a viable feedstock [3D21, 3D25]. Combined, these form many potential

[17] Reference withheld to maintain interviewee's anonymity.

options for feedstocks, with various ways of printing them.

SMEs' extensive contextual and organizational knowledge played a role in narrowing this space. Here, the abundance of specific polymers on cargo missions (to the International Space Station (ISS)), behavior of certain materials in a vacuum environment, and the ease of accessing certain materials on the surface shaped the material tradespace. [3D91, 3D92, 3D96, 3D93, 3D102]. Based on these criteria, two materials came into focus: low-density polyethylene (LDPE), per its abundance in the waste streams of current ISS missions; and basalt igneous rock, per its abundance on Mars (barring the use of a dedicated—but much more expensive—Martian soil simulant) [3D226]. Additionally, SMEs knew that certain materials—particularly water—would be so valuable to sustain the crew that using it as a printing material would be risky [3D11, 3D96]. Quinn stated this position as follows: "I think we would never use water for construction purposes because it's scarce, and you would have higher mission priorities and uses for that water" [3D80].

But SMEs did not just know what materials would be available. Their knowledge also dictated preferences of certain materials over others, which translated into a preference for certain feedstocks. SMEs' preferences would also affect their assessment of the feedstock's feasibility. For example, a feedstock that used water would be less desirable than one that did not.

SMEs embedded their preferences in their competition's scoring system. Here, the formulation team hoped it would push solvers to design feedstocks that SMEs believed would be more feasible. Even in early drafts of the rules, SMEs stated that they "need[ed] a rubric for determining winner of this portion of the [challenge]. Must favor the use of planetary indigenous materials" [3D20, see also 3D110, 3D12]. To do this, SMEs designed a "sliding scale" where the preferred materials[18] received a higher weighting than others [3D91, 3D94, 3D95, 3D96, 3D103, 3D122, P3]. Solvers would stand a greater chance of winning if they designed feedstocks with materials that SMEs preferred: the weights would apply to the

[18] The scale in the rules also explicitly labeled the options that NASA wanted with arrows and language like "most relevant" to further emphasize their importance [3D23].

mass fractions of each material in the solvers' feedstock and played a significant role in the solvers' final scores [3D23]. At the top end of the weighting scheme, receiving the highest score per mass fraction, were LDPE and (crushed) basaltic igneous rock, in line with the SMEs' preferences.

Similarly, the weighting system would also disincentivize certain materials through scoring penalties. In line with the preferences listed above, SMEs applied these penalties to discourage solutions that did not "close the manufacturing loop, [or] doesn't bring in recycling potential, [or] material reuse," per Quinn [3D80]. For example, they included (severe) negative weights for water and specialized, imported materials to make the feedstock work [3D23, 3D25, 3D91, 3D93]. Likewise, using off-the-shelf printing feedstocks–e.g., Portland cement–would not be allowed[19] [3D36, 3D80].

SMEs hoped that the incentives (and disincentives) would nudge solvers towards finding viable feedstocks while allowing teams that could not carry out this exploration to participate. Despite their stated preferences, they did not explicitly forbid any unwanted materials; SMEs believed it was important not to be too prescriptive in the rules [3D95, 3D88, 3D103, 3D122]. By relying on the (dis)incentives instead of exclusion, teams with a terrestrial focus would still see the competition as an opportunity to fulfill their goals—additive construction's potential for efficiency and sustainability in the construction industry resonated strongly with the challenge's partners [3D122, 3D21, 3D94]. SMEs believed that this struck a balance between their planetary additive construction aims and those that terrestrial players aimed for. Ash described this balance as follows:

> So, those were the two goals we were trying to align: the terrestrial benefit and the space benefit. The difficulty was to try and come up with a set of materials that we would score without constraining the competitors. We really didn't want to tell them, "You can't use Portland cement, [or] a certain material, [or] water." We didn't want to constrain them in any way possible. We wanted freedom of thought. That's where we

[19] SMEs, like Quinn, stated that this was meant to discourage teams from, for example, going "to Home Depot and [buying] a bag of cement" to use as their feedstock [3D36]. Developing materials suited for Martian conditions was a fundamental part of this competition and solely relying on existing feedstocks was not going to cut it [3D80]. However, there were no such restrictions on Portland cement's constituent materials.

> came up with a sliding scale where we give a factor, which is a number that varies with applicability to indigenous materials that you can find in space. ... And it's proven to be very successful. [3D94]

Feedstock ratio SMEs' material preferences also drove rules emphasizing the usage of Martian materials. Recall that most cost savings related to ISRU stem from using mass available at the destination versus launching that from Earth. If a team's feedstock recipe only required a small percentage of in-situ material, most of its mass would still need to be transported there. The solution would, thus, fall short of the objectives that SMEs envisioned [3D24, 3D102]. So, to avoid these kinds of feedstocks, SMEs focused on the ratio of ingredients in the feedstock "recipe" to emphasize the usage of in-situ materials [3D1]. As Finley described, they were "just trying to get as much ISRU material in there" [3D24].

SMEs at KSC drew on their experience and experiments to determine the rules. Per above, a low percentage of in-situ material in a feedstock and the solution would not adequately satisfy NASA's aims. However, too high a percentage might result in a feedstock that does not bind or is otherwise not feasible. While SMEs wanted to push solvers towards high fractions of in-situ material usage in their feedstocks, they also wanted to ensure that they did not overshoot this limit. So, to inform the rules, they experimented to understand what fractions of in-situ materials would be feasible. Per one of the SMEs: "we were basically trying to complete the challenge ourselves just ahead of when the actual challenge was happening. That gave us a lot of insight into what is possible or what is not possible" [3D185].

Here, the SMEs decided on a minimum ratio based on their work with polymer-based feedstocks. These ratios are calculated as the fractions of binder to aggregate–in this case, polymer to regolith. While the existing literature and SMEs' previous work showed that a wide range of this ratio was possible, they narrowed it down to a maximum of 30% binder and a minimum of 70% aggregate [3D24, 3D102, 3D103]. This ratio pushed the known limits of how little binder could be added while remaining printable [3D226]. As such, SMEs experimented with various ratios in-house to ensure that this requirement produced a feedstock that would bind its aggregate [3D94]. At the time, Ash was asked whether the rules were realistic, and here is how they described the process of confirming them:

> We went back to the lab, we tried it out, and said, "yeah, 70-30 works. Can it go lower than 70-30?" We did a few more tests and turns out that anything lower than 15% wasn't really working. Any higher than 30 was probably too much binder. So that's how we confirmed that we had good rules. [3D103, see also 3D185]

The 70-30 rule would force the usage of in-situ materials through the high fraction of aggregate materials. Since SMEs estimated that these kinds of feedstocks would use Martian regolith as their aggregate, a high fraction of aggregate would translate into a high usage of in-situ materials—fulfilling NASA's ISRU goals of launching less mass. However, while this rule stemmed from SMEs' work and experiments with polymer-based feedstocks, it would apply to all solutions equally [3D102]. And, per the rules, a "failure to meet this minimum requirement [would] result in disqualification" [3D112, see also 3D23, 3D12].

5.2.3 Printed Material Characterization

In addition to rules surrounding the design of the feedstocks, SMEs also created rules surrounding their performance. Specifically, understanding the mechanical properties of prints with "multiple materials" [3D2, 3D20]. These are needed to understand how materials would behave as part of a structure and further design NASA's systems. For Phase 2, they selected properties that SMEs considered a "first gate" [3D93, 3D101]. Additionally, to ensure efficient and safe construction using these materials, solvers would need to consider (Martian) environmental factors that would impact their materials' mechanical properties. I elaborate below.

Structural performance In the Structural Member Competition, SMEs focused on the materials' basic structural properties [3D101]—material strength, its ability to be printed at high angles, and its tolerances when set. In all, solvers would print a short cylinder, a beam, and a truncated cone. These shapes would then be subjected to compressive, flexural, and their own loads to determine the printed material's strength [3D20, 3D93, 3D101].

Structural performance: Material strength The SMEs drew heavily on standards from the construction industry for their strength tests: the shapes corresponded with ASTM C39, ASTM C78, and (a simile to) ASTM C143, respectively. Despite being designed for concrete, the SMEs appreciated their accessibility and long history. First, these standard tests are used very widely. SMEs "could tell the competitors they could go to any kind of lab to certify the results" as many facilities, both in the United States and internationally, use these to test materials [3D103, see also 3D96]. SMEs reasoned that this availability would bring solvers' testing costs down, thus (potentially) lowering their costs to participate [3D93]. In contrast, standards for testing additively manufactured parts are only now being developed; those that exist have seen very limited usage [3D226]. Second, these standard tests are well-known. Ash related that part of the reason why they "settled on using standard engineering tests [is] because that's what most civil engineers use" [3D103]. Their widespread usage and well-understood behavior increased SMEs' confidence in these tests. SMEs saw them as a first step in characterizing a new material with unknown characteristics. Per Stevie[20], a non-NASA SME from the construction industry who was also part of the formulation team:

> We set the rules of the challenge to the standards that exist today because that's what we know [and] because they're proven ways of testing a specific parameter of a material. As we get into exploring new materials, we start by testing them in the same way. [3D87]

These strength measurements would be the primary yardstick for performance across all levels of the Structural Member competition. The stronger a solver's material was in the tests, the more points they would be awarded; their feedstock recipe would moderate these points, producing their final score [3D23].

[20] A pseudonym.

However, the SMEs understood that these standard tests would not measure these characteristics accurately for all materials. The standard tests were designed for Portland cement concrete. They were not meant to test the (kinds) of materials that solvers would be creating, especially those using a polymer as a binder [3D93]. The tests were, at best, a best-fit standard: intended to provide a uniform measure instead of tailoring to each material that could be submitted [3D93, 3D92]. SMEs knew that they were compromising on the accuracy of the performance of the feedstocks based on the standard measures [3D101]. Ash estimated that "in some cases [the tests] were appropriate, and in some cases, they weren't. But mostly they were" [3D103]. The SMEs saw these inaccuracies as a better alternative than a slew of different tests better suited to the material families submitted by the solvers. The differences in measurement techniques might raise questions of fairness among solvers, which the SMEs wanted to avoid. Finley described their concern as follows: "What we didn't want to have to do is make case-specific decisions on standards and scoring for every team." [3D93].

Structural performance: Material overhang For the final level of the Structural Member challenge, solvers printed a dome designed by the judges [3D23, 3D110]. This dome was challenging for two reasons. First, the top of the dome was horizontal [3D23, 3D103]. Domes, cylinders, or torii maximize inside volume while reducing pressure stresses, making them ideal for habitats on other planets [3D103]. But as the slope increases, the horizontal surface area for the next layer of material reduces. When the slope is zero (or horizontal), the layers connect horizontally and might fall if there is no support.

Second, no supporting structures were allowed in the object after printing [3D23], maximizing the useable area within the habitat [3D103, 3D105]. Usually, these shapes would require support structures for the layers at the top. So, printing the structure without any supporting material seemed impossible; a potential participant even complained that "an FDM-type 3D Printing process could not build this structure without a support structure" [3D122]. However, NASA guidelines for additively manufactured parts advise against having support structures due to the dangers of debris within crewed cabins [3D226]. Additionally, SMEs saw these supports as a waste of the interior space [3D122]. As such, they required that the final shape did not have any, nor deviate from the model in other ways [3D93, 3D96]. As such, the only option, *seemingly*, was to autonomously remove the support structures before the print was finished [3D23, 3D103, 3D122]. SMEs saw this as a difficult task that was important to maintain. Ash described their position as follows: “if we had a competition and allowed support structures, we wouldn’t be advancing the state of the technology. It would be the same as everyone would be doing today” [3D103].

Thus, the dome would test the solvers’ material and printing capabilities. SMEs stated that they “intended for this to be a difficult structure to print” [3D122]. The solvers’ printing system would need to be robust enough to print the dome shape as modeled, relying on either their materials or robotics expertise to dictate their solving approach. For example, others believed that this dome would be hard to print. But despite its difficulty, SMEs estimated—like Ash states below—that the solvers could somehow accomplish this.

> You have to push the boundaries. If it’s completely feasible, then there’s no point in having the competition. So, you have to get to something that you’re 90% can be done, but you’re 10% not sure. And that was [Phase 2’s] dome.” [3D103]

Structural performance: Tolerances Lastly, SMEs also set tolerance criteria on the printed shapes to assess the accuracy of the printing systems. In general, manufacturing an object to a certain accuracy is crucial. If it does not adhere to the required dimensions, it may not fit within its allotted space or perform as intended. This matters for additive construction as well: the imprecision of printing could produce an object that does not conform to what is expected. Here, its dimensions could depend on how neatly a printer can lay down a bead and how that layer behaves once it is laid down [3D89]. Additionally, different materials contract and expand at different rates when exposed to a temperature gradient, meaning the object’s final dimensions might not be the same as the as-printed ones [3D106, 3D185]. In this vein, SMEs wanted to determine the accuracy of solvers’ printing systems.

SMEs imposed a maximum allowable deviation on each object, determining whether their accuracy was allowable. The truncated cone, cylinder, and width and height of the beam received a tolerance of + 7 mm. The length of the beam and the dome structure would receive a tolerance of +/- 7 mm. If solvers' objects did not comply with these tolerances, they would be required to produce new ones or face a zero score for that level [2017-03-02]. At the final level (where printing time was severely limited), the number and magnitude of the tolerance violations could severely reduce the final score—the judges would have the final say here [2017-05-18].

Environmental performance In the Structural Member Competition, SMEs considered including two essential areas relating to the material's performance in the Martian environment: its behavior while exposed to vacuum and its ability to shield against radiation[21]. Their effects on the feedstock's behavior are important to understand and mitigate where needed [3D103, 3D82]. But while SMEs initially considered testing solvers' solutions via analyses, they dropped both criteria from the rules of Phase 2 [3D92].

Environmental performance: Vacuum Since the Martian atmosphere is less dense than Earth's, "vapor pressure is a huge issue," as Finley explained [3D102]. Under these conditions, liquid in the feedstock might boil and evaporate when printed. The printed object will have irregular voids instead of being a solid, and its strength would be considerably reduced [3D65, 3D102, 3D160]. Indeed, experiments conducted by SMEs showed that the material would foam up and form a "muffin top," retaining only a fraction of its material strength [3D103, see also 3D65]. Referring to the performance of that feedstock in those conditions, Finley stated, "it didn't work too well" [3D95, see also 3D103].

Despite its significant influence on the material's printing behavior, however, SMEs decided not to subject solvers to complying with this requirement. In doing so, SMEs would

[21] The latter would be revisited in Phase 3.

lose information on whether and how the material would retain its strength under these conditions [3D82, 3D101]. And since it would not be tested in the relevant environment, it would not mature per the TRL scale [3D94]. Nevertheless, there were several reasons for this decision [3D92, 3D101, 3D102, 3D103]. First, SMEs strongly believed that any such testing requirements would be too costly to impose on solvers if they had to access vacuum chambers themselves [3D80,3D94, 3D103, 3D102]. Ash thought that "it would have probably shut the competition down if we had done that" [3D94]. Second, and relatedly, using one of NASA's test chambers would exceed the 3DPH Challenge's budget [3D101, 3D160]. And lastly, SMEs thought it was too specialized a requirement to impose on teams that were not in the space industry. Instead, SMEs saw it as their responsibility to design towards that environment. As Quinn put it, it was "something that NASA would do on our side" [3D93].

Environmental performance: Radiation The Martian atmosphere does not protect against radiation as Earth's does. This makes it a serious threat to the crew's lives [3D11, 3D93, 3D124]. Thus, structures will need to adequately shield the crew from radiation to be considered habitable. [3D6, 3D124].

However, the SMEs decided not to require solvers to design or test to these conditions. Like the vacuum conditions, SMEs believed that these requirements were quite specialized. Once again, Quinn believed that it would be NASA's responsibility to iterate on "some high potential design or material" in collaboration with the designer [3D93]. As such, the SMEs "[didn't] define radiative environments in the rules, so this [was] really outside the scope of [their] evaluation of materials and structures," per contemporaneous email traffic [3D92].

Environmental performance: Materials scale concerning vacuum and radiation performance The rules for Phase 2 lacked analyses or tests for the Martian environment. However, the materials scale described earlier would still push solvers towards material choices that SMEs believed were more suitable. Specifically, KSC SMEs favored polymers as a construction material partly because they estimated that it would perform better in the

Martian atmosphere than hydraulic cement concrete [3D94, 3D102]. First, polymer binders did not use water. Because they would not suffer from the boil-off problem, SMEs estimated that they would outperform the hydraulic cement concretes. Ash, for example, believed that though "the polymer concretes have never been tested in vacuum, I think that they would do better than the hydraulic concretes" [3D94]. Second, plastics stopped radiation [3D6]. Thus, their use as a building material would include significant protection and its structural functions [3D11]. So, while polymers were already highly rated for their abundance on these missions, the scale *also coincided* with their estimated performance under Mars' conditions. The rules, thus, incentivized solvers towards the options that SMEs believed were better across a broad range of parameters.

5.2.4 Printer Form Factor

The printer's form factor—its footprint and printing method—was also an area SMEs considered gearing towards their application.

Printer footprint For NASA, systems with large footprints are much more costly to field and operate. Their mass and volume mean higher launch costs and more space on a rocket [3D11]. While not as crucial in terrestrial applications, NASA's external partners recognized the benefits of space-saving as well [3D11, 3D180]. Because of this, SMEs considered explicitly restricting the printing system's footprint [3D6, 3D22] or, at least, incentivizing smaller printers [3D11]. For example, one SME on the formulation team commented the following on an early draft of the Structural Member Competition rules: "[W]e should limit the packaged/shipping size of the system. We don't want a great system that could never be moved to a disaster relief area" [3D6].

However, SMEs pushed any such rule outside the context of the 3DPH Challenge. The formulation team decided not to impose any requirement from the space industry on the footprint of the printers. They believed that it would distract from the more important task of demonstrating the printer [3D105]. Instead, the team decided to push the more stringent space requirements until later in the development process. The Structural Member Competition rules merely specified that the printer had to be transported over regular roads [3D23]. Harper summarized their decision not to limit the printer's footprint as follows: "that's not where we want[ed] the teams to spend their time, trying to miniaturize it, trying to– You know? That can happen later once you've proven the technology" [3D105].

Printing methods Mars' reduced gravity environment also imposed difficulties on the printer design. These conditions mean that materials—particularly powders—do not settle as they do on Earth. Powder beds are a common method of 3D printing for terrestrial applications [3D36]. But even with (non-NASA) microgravity research is being done on powder bed printing [3D226], NASA SMEs did not think they could work in their setting. In particular, loose particulate matter during printing could more easily lead to combustion or respiration hazards [3D192, 3D36, 3D91]. Blake put it succinctly: "You can't use a powder bed in microgravity" [3D89]. Additionally, while this method worked well for printing relatively small parts, SMEs did not believe this method could print an object the size of a house [3D95, 3D112, 3D163].

So, SMEs curbed solvers from pursuing architectures that might be familiar to them but (essentially) unsuitable for NASA. The rules explicitly warned against designs that created too much dust or other waste[22] [2017-02-02, 3D112]. SMEs emphasized that these could not safely function in a space context, nor were these safe for people near the printer [3D23, 3D36]. SMEs also forbade manual removal of supporting material for the prints, explicitly mentioning that removal of the powder bed around the printed object fell into this category [3D23]. The competition's FAQ followed suit with further clarifications [3D112]. In contemporaneous email traffic, one SME explained this rule to a fellow team member as

[22] Despite the consensus on the problems with powder beds, SMEs like Quinn expressed an openness to ways of mitigating against the dust issues: ". . . if you can show us how to manage that— We're open to that if you can come to us with an approach of how you would address it, manage it, and ensure safety. . . . It's a challenge not to be too prescriptive" [3D36].

follows:

> Teams do have to address applicability of their manufacturing system to planetary surface construction, and do receive a score on that criteria (which mostly refers to an assessment of whether the process can operate in a reduced or microgravity environment and was included as a way to discourage use of powder-based systems) [3D92].

5.3 Outcomes of the Structural Member Competition

The 3DPH Challenge team saw Phase 2 as a big success. They awarded a total of $701k across the three levels, with the winners taking home $80k, $0K[23], and $250k, respectively. While the number (and variety) of participants was relatively low, SMEs were pleased with the performance of the solutions. After the competition, both the winner and runner-up feedstocks were further tested in-house and aboard the ISS.

5.3.1 Reflections on Participation

While the formulation team's pivot towards the construction industry succeeded in drawing non-space participants, participation was significantly less than the previous one. A total of eight teams participated across the Structural Member competition [3D127]: these solvers submitted at least one solution in one of the three levels. Unlike the Design Competition before it, no non-affiliated teams managed to submit a solution to any level. All teams stemmed from academic or industry backgrounds—five of the former and three of the latter [3D127]. However, like the Design Competition, most participants were not previously part of the space industry: only two described prior space experiences [3D207, 3D208]. The others were decidedly outsiders to this industry [3D90]; these participants talked about how they always dreamed about working with NASA, something that would be "freaking amazing" [3D209]. The teams winnowed down to three in the final round: two academic teams and one industry team.

One cause of the relatively low participation was the high cost of solving. Many teams

[23] No prize money could be awarded to a non-US team, but second place was awarded $67k.

complained that they could not afford to complete the challenge: developing and testing the hardware required for the deliverables of the competition was expensive. Even with the thought that went into reducing the barriers to entry, SMEs on the formulation team acknowledged that "it was a pretty big physical investment," per Harper [3D105]. In a survey after the 3DPH Challenge, solvers reported that developing their materials and creating the associated printer cost more than they were willing to pay. One team who dropped out in Phase 2 described why they stopped participating: "The farther along the competition got, the more expensive it got to participate. We ended up dropping out of the challenge because it was too expensive to continue" [3D98]. Several other teams echoed this sentiment and described the difficulties of acquiring enough capital to fund their developments.

5.3.2 Reflections on Solutions

Solvers demonstrated novel, high-performing materials Participants in this competition produced high-performing materials and meaningful insights for the SMEs. Their innovations covered both hydraulic cement and polymer-based feedstocks. For the former, teams recreated or modified the Portland cement recipe using materials available on Mars. For example, one team drew on their organization's deep experience with Portland cement [3D210]. From their perspective, the risk of pivoting to, from their perspective, an unknown material was too great. Instead, they used their expertise to create a known material in an unfamiliar environment. Per one team member: "It's real exciting to be developing something new. But in this case, we said, 'ok, we know this [material] can do XYZ, how do we get to do it in this application?'" [3D210]. To prove that their recipe could produce the same performance as stock Portland cement, SMEs required that the team demonstrate its performance within acceptable bounds [2017-07-13]. As a result, the team "earned the right and was allowed by the judges to use Portland cement for the competition with a positive 3DP Factor defined by the indigenous factors instead of the negative penalty due for Portland cement" [3D99]. Another team had the same idea but took a different tack: it developed an equivalent to Portland cement that used much less water to achieve a similar material [3D48, 3D156]. Per reports, the SMEs considered these a "significant advancement in the demonstration of cement production from Mars indigenous materials" [P3, 3D99].

For the latter, the winning team—a partnership between Branch Technologies and Techmer PM–produced a high-performing feedstock by combining polyethylene terephthalate glycol (PETG) thermoplastic as a binder with basalt glass fiber as aggregate [3D73, 3D140]. Both binder and aggregate were highly rated materials on the competition's material scale, though using fibered basalt was new to the SMEs [3D73]. Its performance was surprising for two reasons. First, the combination of materials and printing quality also significantly outperformed its hydraulic cement competitors. According to a report on the challenge, the winning polymer concrete feedstock demonstrated a material strength approximately "23 times higher" than typical Portland cements [3D73]. Across the board, SMEs believed "it's a very high strength blend" [3D80, see also 3D94]. More generally, teams that pursued polymer-feedstock options helped "prove out [their] efficacy" in the eyes of the SMEs [3D226].

Second, SMEs were impressed with the printing capabilities displayed by Branch. Ash even exclaimed that they achieved "the holy grail in 3D printing" [3D94]. Conventional wisdom required level 3's dome to be printed with support structures. However, the winning team printed their material horizontally without supports—something that the NASA SMEs did not think these kinds of materials could do. For example, Ash stated they had "never seen it before when you horizontally print, and it doesn't collapse or slump" [3D103]. Jude saw the solvers' performance and remembered thinking, "What just happened! How did they do that! We [as NASA] wouldn't be able to do that!" [3D185]. Across the formulation team, SMEs considered the feedstock, in their words, a "breakthrough" [3D103], an "inspiration to the [KSC] team" [3D130], a "major outcome" [3D80], "absolutely revolutionary" [3D94], and "incredible" [3D93]. The material's performance meant that the team's printing system could produce complex shapes without the complex robotic architecture that other teams required to produce the same shape.

More generally, SMEs were happy that the rules pushed solvers to explore material combinations that they believed were more favorable to their ends. While NASA already had projects exploring planetary additive construction feedstocks and processes [3D63, 3D65], SMEs believed that the efforts of the solvers would help rather than replace them. In line with this sentiment, Quinn described how they saw “the efforts as complementary, rather than competitive” [3D36]. It pushed teams to explore the kinds of designs the SMEs were interested in. Some teams even reported switching from materials they had a lot of experience with to those that gave them a better score [3D36, 3D209]. Overall, SMEs regarded material innovations as a big return on shaping the rules. Quinn, in particular, described how satisfied they were with the overall progress on materials during this phase:

> I think the teams came up with really— Especially in Phase 2, [they] came up with really interesting and different [material] formulations. ... I think that [Branch’s] material [was] just a good, good outcome. And I think [Branch’s partner] Techmer might make that material commercially available now. It’s a very high strength blend. [3D80]

Solvers demonstrated novel autonomous systems Teams whose material could not print horizontally developed novel workarounds to produce the dome shape that the SMEs had laid out. The runner-up—Penn State University (PSU)—impressed the SMEs by demonstrating autonomous printing and removing the needed supporting material [3D189, 3D99]. While a primary robotic arm printed the dome, the team used a second arm to break apart and pick out their supports—thus never needing a manual intervention [3D103]. One of CCP’s weekly reports described the “novel, robotic method” [3D189] like this:

> Penn State’s autonomous removal of the supports they used to print the dome was also novel and a technique they might not otherwise have been developed outside the framework of this competition [CCP147, see also 3D226]

Solution infusion into NASA projects NASA projects infused two solver-created materials following the Structural Member Competition. The winner’s polymer-based feedstock and the runner-up's hydraulic cement feedstock were used in tests or experiments: the KSC team took the former and the MSFC team the latter. This follow-on testing would allow SMEs to characterize the material more thoroughly than the competition. Finley described it as "a direct infusion. We get more information out of it. We can start looking at using that in our systems" [3D95, see also 3D162].

For the former, the SMEs used the solver's feedstock in the in-house polymer printer and adopted their feedstock processing method. First, given the incredible performance of the material in the competition, SMEs were eager to test it in-house [3D162, 3D185]. They procured a batch from the solver (their material supplier, to be exact) and tested it in their lab [3D73, 3D80, 3D99], requiring only minor modifications to their existing printer [3D185]. They learned valuable lessons about the materials printed behavior from their tests [3D130].

Second, the material processing method demonstrated by two teams promised to solve NASA's feedstock homogeneity and safety problems. KSC's approach had been to reduce the raw materials to a powder and combine these at the printhead (while printing) [3D130]. However, it was hard to maintain a homogenous mix of the different raw material powders [3D130]. Additionally, SMEs became concerned about the combustibility of handling powder [3D91]. However, these problems were alleviated by pre-processing the raw materials into homogeneous feedstock pellets before printing [3D91, 3D185, 3D189, P3]. Per a technical report after the competition: "The pellets developed in the competition by several teams eliminate these safety hazards have given NASA important insight into how to use these materials while minimizing danger to mission, crew, and equipment" [3D73].

For the latter, members of the runner-up team sent samples of the material to the ISS for further characterization in microgravity. The team's material had been a hydraulic cement concrete, whose behavior had never been studied in the space environment, specifically exploring the effect of gravity [3D167]. As such, the team developed an on-orbit experiment to observe differences in the feedstock's reactions [3D156, 3D169, 3D174]. Quinn described this as yet another "really good" outcome [3D80].

Solution shortcomings Despite these innovations, some solutions fell short of what the SMEs expected—even the novel ones. First, several teams could not meet the mandated high bar for indigenous Martian material. Recall that solvers' feedstocks needed to include at least 70% indigenous materials. This value stemmed from KSC in-house experiments with polymer-based feedstocks. However, complying with this minimum was much harder for teams that took the hydraulic cement route, who thought they could produce a feedstock that could serve their terrestrial uses as well. Specifically, adding that much aggregate made a viable material "difficult" and "hard," per Finley [3D102]. So hard that it affected the team's participation. Across Phase 2, four teams[24] submitted non-compliant solutions—these were rejected [2017-05-04]. Likewise, one team's score suffered greatly solely because of their choice of materials. As Finley described it:

> If a certain team wants to develop their technology along the lines of 3D printing here on earth with Portland cement, . . . they're not going to want to do that planetary composition. And that's ultimately what hurt [one team] in that last round because they scored low on their materials. [3D102]

Second, SMEs doubted the practicality of (some of) the solvers' feedstocks. The material scale had successfully pushed solvers to design feedstocks using materials on Mars. However, the scale did not incorporate more practical concerns like gathering and processing the materials into their usable forms, which would be extremely important for its usage. Finley "was amazed at the lack of addressing the issue of getting these materials in situ also. That was something I was hoping to get more information on from the competitors" [3D102, see also 2017-05-04]. Practicality was also the main concern for the Martian Portland cement recipe. Though novel, it did not address its supply chain considerations. SMEs estimated that it would require large processing facilities with raw material gathered from disparate places "separated by 1000s of km" to create the cement [3D25, see also 3D102]. Quinn summarized that as follows:

> You can technically make [Portland cement] on a planetary surface, but it requires

[24] One of these four teams submitted a non-compliant polymer-based feedstock.

> a large manufacturing footprint. There's a lot of mental gymnastics associated with saying: "yes, I can actually make this on a planetary surface, ergo you should consider this as an indigenous material." [3D36]

5.3.3 Partnerships Resulting from the Structural Member Competition

Lastly, while SMEs discussed a potential follow-on project with the (level 3) winner, it did not materialize. After the competition, SMEs pushed for a large-scale demonstration of the printing technology. They envisioned printing large water storage tanks as part of KSC's spaceport infrastructure [3D73, 3D137]. However, partly due to other commitments by the solver team, this did not proceed [3D185]. Nevertheless, SMEs were hopeful that such partnerships would eventually materialize. Quoting Quinn: "And I think some of these [teams] may, down the line, work with NASA by virtue of the connections and visibility that they've gotten through the competition" [3D36].

6 Phase 3: The Virtual Construction and Construction Competitions

6.1 Phase 3's Two Competitions

Phase 3 contained two competitions: the Virtual Construction Competition and the Construction Competition. Participants in the former would design a high-fidelity architectural model of their 3D printed Mars habitat. Across two levels of this competition, participants would increase their model's fidelity and the required analyses. Both levels of the Virtual Construction Competition offered $100k in prizes.

Participants in the latter would develop and demonstrate a printing system for larger and (more) realistic structures across three levels. Here, each level tested the solvers' printing systems (feedstock and printer combinations) for their ability to print basic structures to scale (e.g., foundations, pressure vessels). The challenge culminated in a timed print of their habitat designs (scale model) at the Caterpillar Headquarters in Peoria, IL. Per a non-NASA SME on the formulation team, "Phase 3 [was] the most challenging that we've had yet" [3D120]. The prize pots for these three levels were $120k, $300k, and $800k, respectively. See 5 below for a visual summary of this phase.

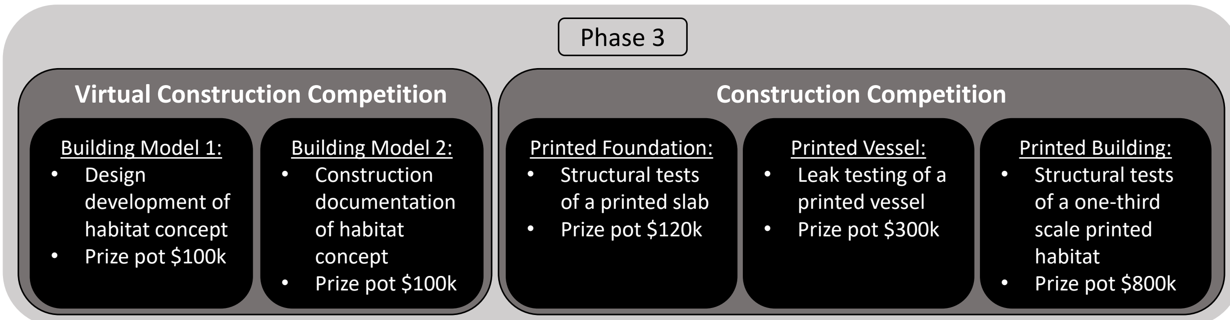

Figure 5: Summary of Phase 3 of the 3DPH Challenge

The two competitions were independent. The deliverables, requirements, and prize awards of one competition did not impact the other. However, participants in the Construction Competition were also required to participate in the Virtual Construction Competition.

The formulation team began their work on this phase in mid-2017. SMEs began formulating the Construction Competition first, then the Virtual Construction Competition in the fall of 2017. Both competitions were opened simultaneously and were held concurrently during 2018 and 2019. The 3DPH Challenge held the final level of Phase 3–the Construction Competition's head-to-head–in the fall of 2019.

Phase 3 would emphasize different areas than the previous phases. Notably, the SMEs deemphasized the importance of materials following a "big internal discussion" [3D80, see also 2017-06-22]. The rules surrounding the feedstock materials in Phase 2 set a high bar, with both good and bad outcomes. They had successfully encouraged the innovations that SMEs were looking for: the Phase 2 winner showed material innovations that took SMEs by surprise. But at the same time, some on the formulation team believed that the rules overconstrained the problem by focusing on polymer binders [3D88]. Additionally, SMEs disqualified several teams that fell short of the stated requirements. Weighing these outcomes, SMEs reconsidered those rules [3D102, 3D73]: while "there [was] general agreement that our Phase 2 materials scale has served us well," the formulation team decided then that these rules needed to be relaxed [2017-06-22, see also 3D80]. Quoting Ash, the formulation team decided: "[L]et's loosen it up for Phase 3.' So, we did" [3D103].

With the deemphasis of materials, SMEs instead shifted the focus towards more important to emphasize areas that had not yet been challenged [3D73]. In particular, both the Virtual Construction competition and the Construction competition would cover three areas of development (coinciding with those described in 2.2.3) [3D11, 3D16, 3D76, 3D96, 3D107, 2017-07-13, 2017-06-22]. The first was related to the printer's behavior: autonomy. SMEs hoped to minimize human interventions during printing and encourage a close relationship between the virtual model and printed object and printing process. The second was related to what would be printed: large-scale objects. Here they hoped to push solvers to scale up the size of the printed objects from those in Phase 2. And finally, an area related to the performance of the prints: bulk structural properties, like pressure retention and surface finish[25]. SMEs would push solvers to accomplish these through a combination of materials and printing processes.

In the sections below, I further explain these decisions and how they infused into the rules for both the Virtual Construction and Construction competitions.

6.2 The Virtual Construction Competition

6.2.1 Establishing the Virtual Competition

At the end of Phase 2, some on the formulation team were concerned about participation in the final phase of 3DPH. While the SMEs were pleased with the winner's performance in Phase 2, they acknowledged that the bar for participation was set very high. Members of the formulation team, like Billie[26], knew the task of creating and demonstrating a printer and

[25]Prints would also be tested for their resistance to impacts, to simulate micrometeorite strikes on Mars. However, the focus of the SMEs—and the points distributions for each level—would be on these two criteria.

[26]A pseudonym.

feedstock system was “difficult” [3D88], requiring a lot of resources on the part of the solvers [3D80, 3D98]. In their estimates, the difficulty would increase by “orders of magnitude” with the scope planned for the construction portion in Phase 3 [3D105]. Here, formulation team members, like Harper, were afraid that few would be able to afford these expenditures, potentially resulting in very few participants in this phase: “there was only going to be a few entities that could probably pull that off. We wanted a broader swath of people to be engaged” [3D105]. As such, some on the formulation team called for something to be done to maintain the interest of solvers that would not be able to complete the physical demonstration [2017-07-20, 2017-06-15].

In response, the formulation team (re)introduced an architectural design challenge as part of Phase 3. Participants would, again, design a habitat built using additive construction technologies. The SME’s vision was to launch a complimentary challenge where the barrier to entry was not as high as the construction deliverables required [3D92]. This competition would allow smaller teams—usually individuals—to participate, broadening the amount/range of potential participants [3D76, 3D105]. A design deliverable in Phase 3 would also reinforce the connections to the architecture community that they created in the Design Competition [3D87].

Like the Design Competition, this challenge aimed to explore the potential designs that could be achieved using additive construction [3D69, 3D120]. The focus would be on novel architectural concepts made possible by additive construction and concepts for its layout and operation of the spaces of the habitat (also called its space programming) [3D87, 3D106, 2017-10-26]. One CCP member of the formulation team envisioned it as follows: “maybe there is a big prize, big-scale competition but alongside maybe a smaller scale competition to bring out more ideas” [2017-06-15].

However, this time, the formulation team would implement rules that would (try to) elicit a consistent quality across the solutions. This way, they would—hopefully—avoid the same pushback and dismissal by SMEs in the Design Competition. The formulation team would also make an effort to clarify what they hoped to see in the submissions. Here, they organized two public webinars, where their experts provided a primer on habitat design, explained their models/rules of thumb that NASA used in their work, and what the competition was asking for [3D120, 3D121, 3D32]. These efforts to increase solution quality contrast starkly with the first phase, where the rules simply pointed to the available reference material [3D97].

Lastly, like in Phase 2, the formulation team reached out to entities they thought would be more likely to participate successfully. Specifically, the competition's emphasis on the Building Information Modeling (BIM) modeling tool targeted those who had experience using this tool. For example, the minutes of the formulation teams' meeting described how they reached out to organizations "in the architecture area or construction management/BIM area" for potential solvers because "they do BIM work" [2018-02-08].

6.2.2 Formulating the Virtual Competition's Problem(s)

Deliverables Wanting to avoid the ambiguous quality of submissions received in Phase 1, the formulation team took a bigger role in shaping what solvers would submit for this design deliverable. The formulation team wanted to remedy the "tension" that Quinn described in Phase 1: on the one hand, a focus on architecture and design–to get broad ideas and participation; and on the other, a focus on space exploration–to get viable habitat designs in the eyes of the SMEs [3D80]. As such, the SMEs took a harder look at the level of detail required for the habitat concepts, hoping that increasing these would improve the submissions' quality [2017-06-22]. For this, they relied on the construction industry collaborators on the formulation team, who looked to approaches within their industries [3D106].

The team settled on a modeling approach from the construction industry called BIM. This approach creates a high-fidelity, virtual representation of the building's physical and functional components [3D32]. They depict the building's systems data, its lifecycle, and how different disciplines can collaborate on its construction [3D121]. When the construction SMEs on the formulation team suggested this approach for the 3DPH Challenge, BIM had already been a "pretty mature technology in the building world," with an established community of practice[27], per Billie [3D106, see also 3D87]. This community had agreed-upon standards of modeling as well as a vision for a common practice of using these techniques as a digital twin to the physical building [3D32, 3D87, 3D200]. In fact, one member of the 3DPH formulation team was a key contributor in developing the BIM modeling standards [3D200].

The known, accepted standards would force consistency in the maturity of the virtual design. In particular, the Level of Development (LOD) BIM standard provides a ladder of increasing specificity for individual elements in a virtual model [3D200]. The higher up the ladder, the more specific information about the element is expected [3D121]; for example, objects range from a symbolic placeholder lacking a shape or size (at LOD100) to sufficient information to fabricate the element depicted (at LOD400) [3D200]. In addition to modeling static structures, BIM's tools also model the (autonomous) movement of equipment and materials during construction, including the building's components modeled at different levels of development [3D32].

SMEs wanted participants to follow this standard and incentivized them to do so. Billie explained how the standard would result in more detailed models: "We use the jargon 'model discipline.' You have to model things appropriately in place, properly label with a recognized level of development" [3D106]. With this commonality in mind, the rules for the Virtual Construction challenge "were actually written to follow the Level of Development standards," per another construction SME assisting with Phase 3 [3D87]. Specifically, the rules awarded points for how well the submission complied with the information content requirements in the BIM standards for the design's two most important subsystems—its structural components and its life support systems [2018-03-22, 3D32, 3D200]. SMEs assigned about 13% of the points for level 1 to comply with the assigned LOD. In level 2, this was about 10% of the total.

[27] The novelty for the BIM community would be applying their approach to create planetary structures [3D106].

These features would allow SMEs to (more) accurately measure the virtual design's maturity and verify (elements of) that design through simulations of its construction process [3D201, 3D185]. The formulation team hoped to better control what solvers would be submitting and instilling "more rigor" in the designs, per Billie [3D106]. This way, they would ensure that the "proposed habitats were realistic in design, materials, and construction and able to be manufactured with [additive construction] technologies," as reports would later detail [3D73].

Design focus Across the two virtual levels, SMEs asked participants to design a habitat yet again. Following the same scenario described in 4.1, the habitat would need to provide adequate living space for the crew of astronauts for the duration of their mission. Being a design competition, the submissions' aesthetics were once again important scoring criteria. Architects with "experience serving on judging panels for significant and iconic structures" evaluated these solutions [3D161, see also 3D32]. SMEs assigned a quarter of the total points in level 1 to the design's aesthetic representation. In level 2, this was approximately 21% of the total.

However, in contrast to the Design Competition, the habitat's space programming was now a major focus. The criteria evaluated how well the design would perform as a living space for the crew. Stevie[28], a non-NASA member of the formulation team, explained that the criteria would test whether solvers "think through not only the different types of programs, the different types of spaces, they really did think about a person's experience in terms of ... [their] public activities and private activities" [3D87, see also 3D106]. It became one of the most important criteria across both levels for the Virtual Construction Competition [3D76]. Its focus was partly in response to the SMEs' concerns about the habitats' functionality in the Design Competition: these "had a lot of variability," per formulation team meeting minutes [2017-06-22]. SMEs assigned a quarter of the total points in level 1 to this criteria. In level 2, this was approximately 21% of the total.

[28]A pseudonym.

Additionally, the solvers' submissions would contain significantly more detail than the Design Competition. In particular, SMEs would focus solvers on three important architectural aspects of their habitat [3D32, 3D120, 3D121]: its structural components, life support systems, and construction process. I explain the rules surrounding these three areas below.

Design focus: Structural components A habitat's structural components provide the enclosure that protects the crew and their equipment [3D32, 3D38, 3D43, 3D120]. The rules specified these as the structure's "foundation, exterior surface, load bearing/pressure retaining walls, etc." [3D76]. In their submissions, solvers would need to show how these components bear the "expected loads" [3D161]: the structure's load as well as its ability to act as a pressure vessel.

The former was related to the loads on the structure caused by Martian physical conditions (e.g., gravity, wind loading) [3D32, 3D76]. While this is a basic requirement for any structure, it is essential here considering the uncertain interactions between (new) feedstocks, material deposition, and habitat geometry.

The latter was related to containing the appropriate atmosphere for the crew's needs, as the Martian atmosphere is less dense than Earth's. While previous Mars mission concepts had incorporated additional structural elements to fulfill this task (e.g., an inflatable membrane) [3D93, 3D87], the SMEs decided on a different approach. As Quinn summarized: "We really wanted to focus this competition on continuous manufacturing, demonstrating a core technology to 3D print an enclosed space, as we wanted pressure retaining structures that were constructed using 3D printing" [3D93]. As such, there was a focus on pushing solvers towards designs and printed objects that were airtight and watertight in both the Virtual and Construction challenges [3D87, see also 3D88, 3D93, 3D107]. In line with containing pressure, SMEs would also push solvers to include, and seal, wall penetrations. Specifically, solvers would design systems to incorporate interfaces with the walls during printing. Similarly, solvers were expected to describe "concepts and methods" for sealing their required penetrations [3D161, 2017-10-26].

The formulation team saw the Virtual Construction Competition as fundamentally a structural competition [3D87, 3D121]. In this vein, the rules required the highest level of maturity for this aspect of the habitat[29]. As one report described it, solvers were to provide "all of the information needed to construct the pressure-retaining and load-bearing portions of the habitat using a large-scale additive manufacturing system" [3D73]. Accordingly, the robustness of these components was also one of the most important scoring criteria. Per meeting minutes, it judged how the submission "documents a practical plan of construction [including its manufacturing processes] as well as habitat suitability for expected loads" [2018-02-15, see also 2017-10-26]. SMEs assigned a quarter of the total points in level 1 to the design's (structural) robustness. In level 2, this was approximately 21% of the total.

Design focus: Life support systems A habitat's life support systems sustain the crew inside the habitat [3D32]. In this competition, this system encompassed air, environmental monitoring, and waste [3D121]. Like the life support systems requirements in the Design Competition, solvers were not required to perform their own sizing calculations. Rather, the formulation team required that their designs include three volumes designated for Environmental Control and Life Support System (ECLSS), summing to 45 ft^3 [3D76, 2017-07-27]. In contrast to the Design Competition, however, solvers were required to design the mechanical, electrical, plumbing, and ducting infrastructure to allow the ECLSS system to function [3D121]—this infrastructure was previously optional. SMEs set this LOD at 200: graphical representations within the solvers' models "with approximate quantities, size, shape, location, and orientation," per the standard [3D200]. Per the rules, SMEs awarded points for "the presence and practicality" of the design of this subsystem—here, solvers could earn about 13% and 10% of the total score in levels 1 and 2, respectively [3D76].

[29] Note here that while solvers were expected to pick "appropriate" materials to use for their printer's feedstock, this area was not part of the scoring process like it was in Phase 2, nor were solvers required to document its recipe [3D161, see also 2018-01-11].

Design focus: Construction processes In addition to modeling the structure and life support "subsystems" [3D32], the formulation team was also interested in modeling *how* these would be constructed. The formulation team understood that the construction of any habitat would need to be (highly) autonomous considering the risks of, e.g., astronauts' exposure to radiation and during construction [e.g., 3D11, 3D103, 3D124]. In the Virtual Construction Competition, this area had two implementations [3D87, 3D88, 3D92, 3D106, 3D121]: advancing the translation step between the virtual model and the printer's processes (bringing these closer together), as well as simulating the flow of (temporary) facilities, equipment, and materials during the construction process.

The former involved exploring more efficient algorithms to turn the virtual model into a tool path [3D92]. In this translation step, an algorithm "slices" the 3D shape into 2D shapes, then forms a path that the print head follows to deposit its feedstock [3D130, 2018-03-29]. This algorithm considers many factors, including deposition rates, drying or solidification times, real-time sloughing, etc. [3D89]. While this translation is common across all forms of 3D printing, no standard processes exist to make this process easy [3D130, 3D165]: quoting Harper, "the industry is not there yet" [3D96]. Additionally, algorithms that print small objects do not translate into large ones—the latter are especially vulnerable to inaccuracies or errors in the printing process. Specifically, the large object's bulk properties may no longer be uniform over the large distances that the print head travels. As Jude explained, "when you're printing something very big, [the tool path] has a huge impact on the overall quality of the structure. [3D185].

SMEs would incentivize solvers to produce and demonstrate these algorithms to spur development, even if they were not printing their objects. The formulation team wanted to push participants to develop algorithms that could perform those translations and "have the printer print it without a lot of other work," per Harper [3D105, see also 3D96]. This was necessary for the teams that participated in the construction phase but incentivized as a bonus for those who only participated in the virtual portion. SMEs believed nudging the virtual participants towards this kind of analysis would close the gap between modeling and the printed structure and improve their feasibility [3D87, 3D96, 3D105].

The latter would simulate the macro construction processes over time, building on the tool pathing algorithms. The SMEs' aim with these requirements would be to evaluate the feasibility of the habitat through its construction sequence [3D106, 3D161, 2018-05-31]. Having created the tool path from the virtual model, solvers would have several pieces of information from which to conduct these analyses, including, e.g., the location of the printer over time and the volume of material required (and when) [3D87]. Solvers would model their 3D printer, its material handling, and the (temporary and permanent) structures it would build on-site during its task in their "4D model" [3D76, see also 3D121]. However, the emphasis remained on the printer's autonomous movements [3D161].

SMEs awarded bonus points to teams who modeled these construction processes. The translation between virtual model and tool path and simulating the flow of materiel were assigned 17% of the total for level 2 of the Virtual Construction Competition [3D32, 3D76, 3D121, 3D200].

6.2.3 Outcomes of the Virtual Construction Competition

SMEs praised both the participation in and solutions from this competition, in contrast to the previous competition on habitat design. A relatively high number of teams participated in both levels of the Virtual Construction Competition. Furthermore, SMEs thought the concepts presented were "realistic" and "novel," per reports after the competition [3D73]. The competition awarded the entire prize pot for each level ($100k)–the winners took home $21k and $34k for levels 1 and 2, respectively. After Phase 3, teams from the Virtual Construction Competition (who also participated in the Construction Competition) began partnerships with NASA teams to design additively constructed infrastructure. These partnerships were, collectively, valued in the millions of dollars.

Feedback from (Potential) Solvers Before they Submitted Solutions SMEs received multiple questions on the pressure-retaining function of the habitat's structure. Using an inflatable bladder to contain the crew's atmosphere is a common concept for Mars habitats: these appear in NASA's trade studies and even in sci-fi depictions of habitats [3D93, 3D87]. Considering the available literature and work already done on this concept, some solvers considered this a "very practical route," as relayed by the formulation team [3D87, 3D93]. Here, solvers wrote in asking if they could use inflatable structures despite the stated rules [2018-01-04]. Several SMEs even stated that it was a feasible option: Quinn, for example, thought, "there's nothing wrong with it. It's a really high utility idea if you're looking at advanced concepts" [3D93, see also 3D92, 3D87].

However, this did not line up with the intent of the challenge. Solvers would not be (designing systems to) print pressure-retaining objects and structures by incorporating these inflatable structures in their designs. Instead, they would transfer the pressure retention function to another part of the habitat. This is not what SMEs wanted. Contemporaneous documents show SMEs being aware of the tension faced by solvers; they even acknowledge that it would be difficult to do with the polymer feedstocks that KSC was most interested in [3D81, 3D92, 2018-07-19, 2018-08-02]. SMEs knew this was unconventional and hard [3D88, 3D93, 3D107] but decided to stick with their decision. Per contemporaneous emails between formulation team members: "There's nothing inherently wrong with [that] approach in a broader sense, but the intent of the competition is to 3D print a pressure-retaining structure" [3D92].

To make their intent clear, SMEs explicitly discouraged concepts that relied on inflatables to perform the pressure-retaining function. They expressed this in messages to teams and public FAQ documents [3D161, 2017-12-20, 2018-01-04, 2018-04-11]. In recalling these interactions between solvers and the formulation team, Quinn summarized it as follows:

> So, we really emphasized that in the rules to try to drive people away from using inflatables. And try to maintain that consistently throughout the competition because we would get questions about inflatables from teams. I remember we put out a couple

> of FAQs about it. Just emphasizing that the intention of the competition is to 3D print a pressure-retaining structure and that that is the definition of this challenge. [3D93]

Reflections on Solutions The formulation team was pleased with the quality of solutions in this competition. In particular, SMEs recognized and praised the increased fidelity of these solutions compared to those in the Design Competition—and credited the rules for driving solvers towards these details. The increased fidelity allowed them to better assess the designs (specifically their layouts) and label designs as novel when merited [3D73, 3D87, 3D106]. Along these lines, SMEs reported that "the level of detail required as part of the BIM competition ensured that proposed habitats were realistic in design, materials, and construction and able to be manufactured with [additive manufacturing] technologies" [3D73]. Furthermore, members of the 3DPH Challenge team expressed, yet again, how impressed they were with the quality of the visual products and commended how it helped them communicate their plans within NASA and to the general public. Billie described his view of the Virtual Construction Competition solutions as follows:

> NASA got huge infusion out of [the] Virtual [Construction Competition]. Those images and videos that came out of that, that's all over NASA websites and NASA space [outreach]. If you have a Zoom meeting with [some NASA SMEs on the formulation team], you'll see the images in their background. So, the visual quality, the engagement of the general public, and— [getting the public to think:] "I want to go live on... Look at that cool building. I can live in that?" I think was huge. [3D225]

Despite this quality, there was one area where some solutions fell short. Some teams did not follow the SMEs' intended design exploration, both levels 1 and 2. In level 1, some teams presented submissions where the printed object did not function as the main pressure vessel, despite the rules to the contrary [3D76]. Instead, they submitted a design that relied on an inflatable structure: they were to "print a 'habitat' which is a sealed structure – not printing a "shell" which is only protection, not a sealed habitat," per formulation team meeting minutes [2018-08-02, see also 3D92]. Formulation team members summarized the solvers' thinking here as follows: solvers thought, "we can't really 3D print at scale, we know we can't make it air and watertight, and we know that there's perchlorates in the soil, and we don't know how harmful they are. ... So it's not viable" [3D87]. Though SMEs thought these designs could be feasible, they believed these did not push additive construction technology forward. Per their emails, solutions that use inflatables "do not address in-situ 3D-printed construction challenges such as sealing penetrations in a printed structure" [3D92].

Solvers using inflatables in their designs was of "significant" concern for the judges and the SMEs [2018-08-02]. Their meeting minutes captured how they believed teams were skirting the challenges of pressure retention in 3D printed structures: "All the pressurized parts are brought from Earth so [the teams] don't have to deal with sealing and such with printing" [2018-07-12]. SMEs, quoting Quinn and Billie here, also stated how this design "really wasn't what we were looking for for this competition" [3D93], and how they were "kind of stuck judging that. It isn't really what we wanted" [3D88].

SMEs issued penalties and clarifications to avoid this going forward. Per Quinn: "We really emphasized that in the rules to try to drive people away from using inflatables" [3D93]. Teams that presented inflatable structures would only be eligible for half the Robustness points for level 1 [2018-07-12, 2018-07-17]. To counter these designs in level 2, SMEs also issued additional clarifications. SMEs communicated to solvers that "teams that relied on pressure retaining structures not designed to be constructed using 3D-printed materials were judged to be not as robust as those that used this construction method" [2018-11-15]. Further, to avoid large structures that would contain all of the habitat's pressure, they specified that any "membrane" used to improve the sealing properties of the teams' structure "must be autonomously placed and make up less than 2% of the structure by volume" [3D161].

Reflections on Participation Once again, the formulation team succeeded in attracting (relatively) many participants from non-space backgrounds. The formulation team's strategy to "try to show that the barrier to entry [to the Virtual Construction competition] is low and to get more participants" seemingly paid off [2018-02-08]. Around 18 teams[30] submitted entries to the first level and 11 in the second [3D127]. Like Phase 1, and in contrast to Phase 2, there was a (more or less) equal spread of academic, industry, and unaffiliated teams [3D127]. The latter were hobbyists, experts in design, architecture, and BIM who participated because of overlapping interests [3D202]. Here, one participant—an architect with an amateur interest in space–described why they decided to participate:

> I was familiar with the first phase and thought it was really impressive. And the second phase. But the third phase, being focused on BIM as a platform, really sat squarely in my interests and career focus. And put that on the backdrop of "I'm really interested in space." I would be dreaming of how to build Martian habitats regardless of the competition, so being able to put this to practical use has been really cool. [3D203]

Partnerships Resulting from the Virtual Competition Two NASA collaborations resulted from the work that solvers conducted in this competition. While the scope of their work covered more than the architectural design themes dealt with in the Virtual Construction competition[31], I will emphasize those below.

The first was between the winner (of the Virtual Construction Competition level 2) and an MSFC team working on new printing system concepts for the moon [LE3, 3D159, 3D215]. In the Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) partnership, the solver team would develop additive construction architectural concepts like in this competition [3D186]. The partnership's press releases described their vision as "a 3D-printed, sustainable lunar habitat that will be capable of protecting inhabitants from exposure to radiation, extreme temperature differentials, and the constant pelting of micrometeors" [3D186]. Per an MMPACT team member (and an SME on the formulation team)[32]: "SEARCH is on our team now as well, and they're doing a great job in coming up with architectural concepts to print." NASA and the Department of Defense awarded the

[30] Available documentation differs in how many teams submitted solutions: CCP's contemporaneous documents mention 18 [CCP173, CCP174], 3DPH Challenge summary documents mention 16 [3D127] or 18 [3D69], and documents from SMEs mention 17 [3D201].

[31] Both partnerships described below also set out to develop and test relevant technologies for the lunar surface [3D154, 3D155, 3D159, 3D172, 3D215]; I return to these in the 6.3.4.

[32] Reference withheld to maintain interviewee's anonymity.

partnership approximately $14.55M; the architectural concept portion was a small part of this amount [3D135].

The second collaboration was between a KSC team and a participant in the Virtual Construction Competition (and winner of the final level of the Construction Competition). Like their MSFC counterparts, the former also worked on printing systems for the lunar surface [3D155]. In the REACT project, part of their intent was to develop an architectural concept: an additive constructed, unpressurized radiation shelter for the moon [3D185]. NASA awarded the partnership approximately $627k; the architectural concept portion was a small part of this amount [3D213, 3D214].

The NASA teams felt that a closer relationship with the solver team benefitted their work. SMEs felt like they could better engage and coordinate work from these outsiders in this way [3D160]. Here is how one of REACT's team members described their view of the partnership[33]:

> They're an architecture firm. We're not. We're not architects. We do have some architects, but not very many. How can you say that you're going to develop infrastructure in a lunar settlement without the help of architects to actually design it? It doesn't make sense. It's not correct. ... Let's try to focus [the solver's] architectural capabilities and structural engineering firm support in a direction that will support a NASA mission objective, which is that anti-radiation protection.

6.3 The Construction Competition

6.3.1 Establishing the Construction Competition

In Phase 3, SMEs emphasized the technical areas that had not been challenged in previous phases. Specifically, the robotic architecture required to print large structures and autonomous capabilities to go along with them had not received the same attention in the previous phases. Here, SMEs decided to pivot away from materials: there had been significant developments in materials in Phase 2 and the lack of demonstrated performance in the other areas.

[33] Reference withheld to maintain interviewee's anonymity.

Instead, the Construction Competition would challenge participants to design and demonstrate large-scale, autonomous 3D printing [3D69, 3D76, 3D103, 3D108]. NASA needed systems that could print objects on the scale of a small house: the order of magnitude of the structures they envisioned building on other planets [3D34, 3D103]. Since the start, SMEs had always wanted solvers in the 3DPH Challenge to demonstrate this capability [3D2, 3D6, 3D11, 3D12]. The formulation team expected this task to be the most expensive and intensive of all, so it became the challenge's finale, with the biggest purse [3D11, 3D81].

To push solvers in that direction, the scale of objects and the degree of autonomy would ramp up in this competition. While the Structural Member Competition's objects were, at most, desktop-sized (about 1 m^2), the Construction Competition's objects would increase towards full scale (about 100 m^2) [3D96]. Similarly, previous phases had not required any in-depth explanation of the autonomy of their systems (like Phase 1) [3D17] or only operated over a short time printing a simple shape (Phase 2) [3D23]. Instead, Phase 3 would strongly emphasize the solutions' autonomous performance in printing something complex and at scale [3D76].

The Construction Competition followed suit with the shift towards the construction industry in the previous phase. First, the 3DPH Challenge team made a concerted effort to promote the 3DPH Challenge to the construction community. Here, they were a highlighted guest or keynote speaker at several large, construction-centric conferences [2017-07-13, 3D108, CCP103, CCP124, CCP126, CCP132]. "Anyone who's anyone in the construction industry [would] be at [these] conference[s]," per a CCP team member [3D116]. They received significant interest at these conferences, and per summaries, "the feedback from the attendees were extremely positive" [CCP154, see also CCP152]. Note that this outreach happened in addition to the outreach through the CCP's regular channels and public webinars [3D116].

Second, the construction industry SMEs that had played a role in shaping the rules for Phase 2 took on a more prominent role in this formulation process. They influenced the kinds of tests that they would require solvers' systems to perform, the metrics they would use to judge the solutions, and the relaxing of the space-focused rules of Phase 2 [2017-06-15, 2017-06-22, 2019-01-31, 3D88, 3D105]. This way, these construction SMEs strongly shaped the challenge, making it more attractive and familiar to their industry [2017-06-22].

6.3.2 Formulating the Construction Competition's Problem(s)

Deliverables: Printing large structures The deliverables for this final competition would be large, printed objects[34]. Drawing on their experience with ACME and other associated robotics projects, the SMEs were convinced that existing, small-scale printing demonstrations (including those in Phase 2) would not address the technical challenges they were facing [3D80, 3D96]. If solvers printed the size of structures that the SMEs were interested in, it would increase the relevance of the incoming solutions to the SME's work [3D94]. Even early on, the challenge team felt they "had to establish some minimum amount of square footage volume to make sure competitors wouldn't create a system that we couldn't use," per Riley [3D11]. Similarly, Jude described the uncertainties in extrapolating from the "desktop scale":

> How does this scaling up of this portion work? How can we scale it up? You have a whole different range of problems when you scale up than you do when you are printing at a little desktop scale. How can we control this system so that we get a good print? [3D185]

Increasing the size of the printed object(s) meant solvers would need to overcome the related technical hurdles. SMEs wanted to see various designs that could print habitat-sized objects to understand what systems might work and what might not [3D36]. Note that the performance of solvers' printers from printing small, desktop-sized printers in Phase 2 would not (convincingly) demonstrate their ability to print much larger structures[35]. Exploring, and then downselecting from, the solvers' new designs for Phase 3 would be a meaningful

[34]Recall that solvers who participated in the Construction competition would also need to participate in the Virtual Construction competition [3D96], increasing their workload significantly [3D98].

[35]The Virtual Construction Competition incentivized solvers to tackle some of this modeling task [3D89].

step forward for this system's development [3D27, 3D36, 3D89, 3D94]. As such, the SMEs required large-scale prints, pushing solvers to design and develop the printing systems needed to address NASA's need.

However, despite the importance and relevance of printing large structures, solvers would not be required to print to the size required for a Martian mission. Initially, SMEs envisioned the last deliverable (of the 3DPH challenge) to be a full-scale print of the habitat [3D11, 3D12]. Specifically, solvers would print 1000 ft^2 spaces based on the requirements for crew space laid out early in the formulation process [3D4].

The vision persisted well into the formulation of Phase 3 until it was questioned for its practicality and scaled-down. Here, the construction industry SMEs, joined by some NASA SMEs, raised concerns about the resources required to produce these structures. Specifically, the costs of construction (e.g., material, power, time) would—in their minds—exceed what solvers would be willing to spend for the challenge [3D80, 3D94, 3D96]. Some on the formulation team even questioned the need for the full-scale requirement, wondering whether the technology required for a smaller-scale print could successfully complete the full-scale one [2017-08-31, 3D81]. Additionally, Caterpillar—reprising its role as the site for the final level of the competition—was concerned about the logistics of several teams needing to build and demolish the equivalent of a "small three-bedroom house" [3D94, 2017-08-31]. Instead, the SMEs settled on a minimum area of 10.33 m^2 (or 111 ft^2), down from the full-scale design of 93 m^2 (or 1000 ft^2) [3D76]. Ash summarized the decision as follows:

> At the beginning, we said 1000 ft^2 because that's about the size of a small home. And then we realized the logistics of having a competition with that much material, and that size of a structure was prohibitive in cost for the competitors and in logistics for us and Caterpillar. So, we went down to a third scale. So much smaller, about 200 ft^2 [*sic*] total [3D103].

Nevertheless, the object's size would still make the Construction Competition a "high-risk technology development opportunity," per Quinn [3D36], even with the scaling. Printing on-site at Caterpillar—with its limited accessibility to outsiders—meant that solvers would need to complete their objects within the competition's window at their facility. Thus, the challenge solvers faced was printing their large structures quickly, requiring printers with high material deposition rates. To put this in context, SMEs had only just attained acceptable deposition rates of their printer to produce—and model the production of—comparably large structures in the ACME project [3D65, 3D89, 3D180]. Per Quinn, it was *this* requirement that made the competition more challenging than any phase before it:

> Ademir: . . . What is it that makes [the Construction Competition] difficult?
>
> Quinn: It's the deposition rate— The amount of material that you have to be able to put out during the time frame to actually reach the square footage that we dictated. It's also that there is not a lot of room for margin of error. You have 30 hours, so you don't have a lot of time. [3D81]

Deliverables: What solvers would print The printed objects within the Construction Competition would progress from small structures to large and more complex ones across its three levels. Participants would be required to print bigger and more intricate/complex structures [3D76, 2017-07-13, 2017-07-20, 3D120]. Much like the Structural Member competition in Phase 2, SMEs chose these with particular performance tests in mind (explained in the section 6.3.2 below). First, in level 1, solvers were to print a 6 m^2 horizontal slab (with a wall interface), simulating a slab on grade foundation for a building [3D76, 3D120, 3D88]. Solvers would also need to print test specimens to test their printed material's characteristics on the same scale as those used in Phase 2. Next, in level 2, solvers printed a large cylinder–approximately 3 m^2 by 1.5 m, including a larger foundation [3D76]. This structure, referred to as a "bucket" [2018-12-13, 3D88, 3D120], would simulate a (hydrostatic) pressure vessel. Finally, in level 3, solvers would print their designs[36] for their habitats at a third scale, with the minimum area described earlier [3D76, 3D120].

[36] Because of scaling, certain features of the full-scale designs would not fully reflect the habitat. SMEs understood and were ok with some inconsistencies between scales as long as the simplifications were acceptable [2018-04-05]. For example, smaller penetrations might fell outside of the print resolution. Per Billie, teams were "supposed to print the structural or pressure retaining components. And since it's a 1/3 scale, they can leave out the small penetrations, but they need to include the bigger ones" [3D88].

Autonomy The autonomy of the printer was the most important criterion in the Construction competition—"the biggest focus of Phase 3" per a member of the CCP team [3D29, see also 3D80]. Similarly, while the goal of minimizing human intervention in the printing process had been a part of every competition in this series [3D122], this time, "we really wanted to push the autonomy," per Harper [3D96]. To emphasize this importance to solvers, SMEs awarded over 40% of the available points to the printer's autonomous behavior in each level, far surpassing other areas like materials or strength [3D76]. As relayed by Harper, SMEs firmly believed that its importance should be communicated with the scoring distribution "because teams are going to go after the maximum points" [3D96].

Why this emphasis? NASA highly values the ability to pre-deploy these structures: considering the risks of being on the surface of Mars, any such structure would, ideally, be waiting for astronauts to inhabit as soon as they land [3D124, 3D29, 3D81]. Communication delays with that planet would mean that the printers would need to operate (mostly) autonomously [3D103, 3D94]. Even if pre-deployment is too high a bar, high levels of autonomy would "massively" reduce the risks associated with construction for astronauts [3D80, see also 3D94].

Throughout the Phase 3 formulation process, there were discussions into how high the bar for autonomy would be set in the challenge. Early drafts considered perfect autonomy, in line with the ideal for a Mars mission. Summarizing the formulation team's discussions, Harper stated they would have loved to see solvers demonstrate this performance: teams would "come in, push the button, and walk away for the day. And print [their] structure. That would be the ideal." [3D96, see also 3D105]. But they knew that requiring solvers to perform to this bar (and no lower) would be too stringent. First, SMEs like Quinn and Ash believed it would be too difficult and too costly for the solvers to achieve this: this would be "a very tall challenge" [3D81], as autonomous systems are "very hard and very expensive" [3D103, see also 3D6, 3D80]. Second, SMEs also believed that a stringent requirement for autonomy would not make for a worthwhile competition [3D105]. If solvers were eliminated after their first failure, it was likely that no one would finish. Ash described how the formulation team "didn't want them to put all that time and effort in, come to Peoria, and get knocked out in the first two minutes because they had to do a manual intervention." [3D103].

With zero interventions remaining the ideal, the rules would penalize solvers whenever they interacted with their printer. Specifically, when they touched their robot to resume printing, it would result in more severe penalties than when they did not—termed physical and remote interventions, respectively. Harper and Ash explained these differences as follows. In the former, teams would "have to go out there with a shovel or hammer or wrench and adjust something" [3D105, see also 3D81]. In the latter, teams may have to "change a variable, or reboot the computer, [or] do a software adjustment" [3D103]. While both interventions were unwanted, SMEs deducted more points for physical interventions: requiring remote interventions might reduce the printer's efficiency, but physical ones would pose severe problems on Mars [3D103, 3D105].

Printed material characterization By deemphasizing materials, SMEs changed their importance in this competition. First, materials took a backseat: as described above, SMEs shifted the attention from materials to autonomy with an updated points distribution. In the Structural Member Competition, many points depended on material selection. In contrast, less than 10% of the total points in the Construction competition were available for material selection [3D76]. Note that Phase 2's scale for material scoring—described in 5.2.2—carried over to the Construction competition. The scale (yet again) served as a guide to show solvers what kinds of material NASA preferred and to score solvers' submissions.

Second, SMEs also lightened the burden associated with materials. They believed developing a new feedstock, printing larger objects, *and* demonstrating high levels of autonomy within one competition "would have been too much" [3D80, see also 3D92, 3D103]. In response, SMEs removed the requirement for a minimum ratio of aggregate to binder in feedstocks, removed the heavy penalties on imported materials and water, and allowed previously discouraged, non-optimal materials–specifically Portland cement—to be used [3D25, 3D81, 3D92, 3D93, 3D101].

SMEs believed that these changes would give solvers the leeway to ignore this category if they found it too onerous to comply. Per their conversations at the time, SMEs understood that the rules for Phase 3 "(probably) [wouldn't] do anything to advance state of the art in terms of materials" [3D92]. But they believed that relaxing these rules on materials would give solvers room to focus their efforts elsewhere [3D81, 3D93]. Quinn recalled how the formulation team thought about this tradeoff: "I think that was the overarching rationale was [as follows]: 'even if we don't have teams developing new cementitious materials, they can make technology advancements in other areas'" [3D80].

The deemphasis also changed what kinds of material characteristics SMEs would look for. Less emphasis would be placed on materials generally, but the attention would also shift from the feedstock's recipe to its printed behavior. Quinn described the shift in focus as follows: "It's really just, like, looking less at what material might people use and more about what we are actually worried about. What would we want to see in terms of performance of materials in the application of the habitat" [3D93]. For the feedstock's structural performance, SMEs characterized the printed structure's ability to retain pressure as well as its surface properties. For the feedstock's environmental performance, SMEs revisited the Martian conditions that would affect the printed structure. However, despite extensive knowledge of what the habitats—and their inhabitants—would go through on Mars, they decided to limit the tests to two: micrometeorite impacts and extreme temperature cycles. I explain the structural and environmental performance characteristics below; they are discussed per their share of the score in the Construction Competition.

Structural performance: Pressure retention Across both competitions in Phase 3, SMEs wanted to drive the printed structures to retain pressure. The Construction Competition operationalized this in two ways: printing a hermetically sealed structure and creating preplanned penetrations in a printed surface (instead of relying on rework) [3D189, 2017-07-14]. SMEs hoped solvers would demonstrate these with their printers and not (overly) rely on prefabricated parts [3D105]. In this vein, inflatables would not be allowed [3D87, 3D76]—much like the Virtual Construction competition. However, autonomously installing smaller elements to incorporate the penetrations or applying a sealant coating onto the structure's printed surface would be acceptable [2018-01-11]. SMEs believed that demonstrating these abilities would be "challenging," as they depended heavily on the material and how well each layer bonded to the others [3D88]. Success would mean a significant gain for the field of additive construction [3D80, 3D81]. Per Quinn:

> [We emphasized] that the intention of the competition is to 3D print a pressure-retaining structure and that that is the definition of this challenge. . . . We also really wanted to draw people to seal penetrations because that was seen as something that would really advance the state-of-the-art for 3D printing for construction. [3D93]

Solvers would demonstrate their pressure retaining capabilities across two levels in the Construction competition. The formulation team found tests that approximated the desired behavior instead of ones that would more accurately reflect the use case of the habitat [3D108, 3D165, 3D189, 2017-08-03]. This decision came down to safety: the construction industry had long used these kinds of tests in cases when failure of the vessel was a possibility, and the formulation team would employ that same thinking here. As one of the construction industry SMEs, Blake described the risk as follows: "You don't want to use compressed gasses, 'cause they're really bad when things go wrong" [3D88].

Solvers would try to avoid leakage between deposited layers and leakage around their penetrations in both levels. In level 2, SMEs tasked solvers with printing the "bucket" and filling it with water. Its pressure-retaining performance would be measured by the structure's leakage rate [3D76]. In level 3, SMEs would deploy a smoke bomb inside the printed scaled models and deduct points for any escaping smoke [3D76]. Across levels 2 and 3, the points available for this performance were less than 13% of the total.

Structural performance: Surface properties SMEs also imposed tests on the printed structures' surface properties, specifically how flat and level their prints could be. Much like the tolerance requirements in Phase 2, SMEs wanted to measure the different printing systems' accuracy. Specifically, measures for flatness and levelness—derived from measures for concrete–would verify that their foundation could function as intended: a slab with a slope of zero and minimal elevation changes across its surface. Here, SMEs decided to relax the Phase 2 tolerance criteria. SMEs did not prescribe a tolerance band for the slab, assigning a zero score to solutions that could not meet that [3D88]. Instead, more points were deducted for greater deviations from the ideal [3D76]. The scale would award more points for smaller depressions and slope to "measure the quality of how you print," per Billie [3D88]. For the slab-on-grade structure in level 1, the total amount of points available for flatness and levelness were 7% and 2%, respectively [3D76].

Structural performance: Material Strength Lastly, to provide a basic picture of the materials' characteristics, SMEs incorporated the material strength tests from Phase 2. Specifically, solvers would print pre-specified test samples, which would be subjected to compressive and bending loads. The level 1 rules instructed teams to, once again, perform their compression testing through a third-party lab using the standard ASTM C39 test. However, the beam bending test would be performed on-site at the level 3 face-off. Both tests retained their tolerance requirement from Phase 2. Total points available for these tests—related to the forces they could withstand without failing—did not exceed 9% of the available points per level, with an additional 0.5% awarded for complying with the tolerance requirements (in level 1).

Environmental performance: Impact resistance Micrometeorite impacts are a significant factor for large structures on Mars. Mars' thin atmosphere means that (some) objects do not burn up upon entry like on Earth. As such, their high kinetic energy could seriously damage the habitat. NASA SMEs have studied these impacts, particularly their role in habitat design [3D32, 3D80]. As a result, NASA has some information on the meteorite flux, energy, and various materials' resistance to impact [3D92, 3D93 3D185]. In this vein, the ACME project had made strides in testing how well different 3D printable concrete mixes could withstand hypervelocity impacts [3D204, 3D63]. "But that's still a long way to go," per Blake, who was also a member of that project [3D89].

Because of its potential to harm the habitat, SMEs wanted to incorporate this criterion in Phase 3. However, achieving realistic speeds with comparable objects requires highly specialized equipment and testing facilities—in this case, NASA's hypervelocity testing lab at its White Sands Test Facility [3D93, 3D204]. As such, performing these tests is expensive and, per SMEs, also an undue burden on solvers in the 3DPH Challenge [3D80]. Like testing materials in a vacuum, Quinn again believed that this was their responsibility, something that NASA would have to take on "if you were actually going to fly the material" [3D93, 3D226].

Instead of the standard impact tests, SMEs turned to drop tests. Here, prespecified weights would be dropped from prespecified heights onto the printed structures in levels 1 and 3 [3D108, 3D121], removing the need for specialized equipment. SMEs would measure the performance of the solvers' structures by how well they withstood multiple impacts, i.e., how the weight cracked, deformed, or perforated the structure [3D76]. The points available for the submission's impact performance in levels 1 and 3 were 9% and 5% of the total, respectively.

Environmental performance: Extreme temperature cycles Temperatures on Mars can swing from 20 °C to -125 °C [3D192], placing significant strains on objects on the surface. Through this range of freezing and thawing[37], a printed habitat could expand and contract quite severely depending on the material(s) used—determined by the material's coefficient of thermal expansion [3D73]. Cycles of expansion and contraction could cause damage to the habitat or worsen existing thermal stresses left by printing. In the vein of focusing on the

[37] Abbreviated as "freeze/thaw" [2017-10-12].

material's performance as a building material for a habitat over its composition (as described in Printed material characterization). Quinn summarized their decision as follows:

> [We had] high-level philosophical discussions on what does a habitat have to do. So, one of the things that it has to do is withstand temperature swings and freeze/thaw cycles. So, we decided to put that one in there. [3D93]

Unlike the impact test, some facilities could subject test specimens to the relevant conditions. Here, the formulation team drew on a standardized test in the construction industry [3D105]: the ASTM C666 test subjected test specimens to freezing and thawing cycles [3D76, 3D92]. Much like in Phase 2, SMEs reasoned that the costs of solving could be reduced by leveraging non-space, third-part labs that could test for the relevant parameter [3D102]. Quinn summarized this decision as well:

> [ASTM C666]'s viewed as a more accessible test. It's commonly done in construction. So, we felt like that one, teams would have access to a test lab here to actually execute that test and that the cost of that wouldn't be prohibitive [3D79, see also 3D93].

But the SMEs traded the ease of solving for the utility of the result. Much like the ASTM tests conducted in Phase 2, this standard test was also formulated for the performance of cement. Quinn, like others, believed that the differences between polymer-based feedstocks and the cement-based ones meant that the freeze/thaw test "[wasn't] necessarily the most appropriate test" [3D101, see also 3D73, 3D93]. The testing labs that solvers approached reported that they "don't even know how to run a freeze/thaw test on [a] mostly plastic-based material. And if [we] do run it, it's just going to break" [3D92].

In the end, the competition dynamics won out, and solvers would only perform one test. Some SMEs on the formulation team wished to have tests tailored to specific material families [3D101], even suggesting alternatives to use alongside the ASTM C666 test [3D92]. Nevertheless, it was more important to judge all submissions equally to them. In their contemporaneous emails, SMEs expressly stated that they "don't really want to open the door to having to make case-specific decisions on standards and scoring for every team" [3D92]. The ASTM C666 test would be a best-fit across the material tests, and straightforwardly, higher performance would result in a higher score for this criteria. Billie described their thought process as follows:

> Some of the materials that were developed, especially in Phase 3, are not conducive to standard tests. [It's a double-edged sword:] you want standard tests, so you don't want to make up tests to match the materials. But if the material doesn't match the standard tests, you say [to the solvers:] "do the best you can, and we'll figure out what your score is." [3D88]

Across levels 1, 2, and 3, SMEs assigned no more than 9% of the total per level for this performance (it decreased to 5% in level 3).

Environmental performance: Material safety Any material used to build habitats for the crew will need to be safe to be around. In the space context, material safety comprises three factors: flammability, toxicity, and its ability to block radiation [3D80, 3D11, 3D185]. All three are crucial for the crew's survival [3D79, 3D32]. But none were included in the Construction competition. Quinn described how "they are tests that are very difficult [to] execute, ... really expensive, and a lot of test labs that are accessible to teams wouldn't have the capability to do these tests" [3D79]. As such, they made cuts to tests related to material safety, aiming to make it easier (and less costly) to participate. Because of the expense and the uniqueness of these performance levels, NASA would retain the burden of addressing these criteria in a follow-on development [3D80]. Quinn again explained their view of whose responsibility these criteria were:

> This is a public-facing competition, so you can't necessarily load it up with these highly specialized requirements. If we decided to move forward with a specific habitat design or specific material, that's something that NASA would do on our side. [3D93]

Flammability and toxicity NASA has strict requirements for testing materials that could be flammable or toxic in a crewed environment. Per Quinn, "every material that flies to space has to undergo both of those tests" [3D79]. These are of particular concern with new materials, such as those created for (and processed by) 3D printing [3D93, 3D101]—for example, some teams are concerned about off-gassing of volatile organic compounds and nanoparticles [3D185]. SMEs described how they tried to incorporate these criteria [3D93, 2017-07-20]. Quinn even wished they had a bigger budget to perform "flammability testing of the teams' material, or toxicity testing, or vacuum outgassing testing" on the incoming solutions [3D101]. But, as Harper described, "in the end, we just all agreed that the value doesn't justify the expense" on the solvers' side [3D105].

There were several arguments against including them. First, these characteristics are tested to levels that are highly specific to the space industry [3D93, 3D101]. While the formulation team tried to find equivalents, they could not find other labs that would test these effectively, requiring specialized tests and facilities. Subjecting solutions to the more commonly available ones would be a waste of resources [3D105]. Second, running these tests at NASA is expensive and difficult to access, even for NASA SMEs (these performance characteristics are also tested at the White Sands testing facility) [3D101, 3D93, 3D95]. And lastly, SMEs could reevaluate and modify the materials at a later time. For example, SMEs thought they could add something to the feedstock later to ensure that it better complied with the flammability requirements [3D80]. For example, Quinn described their nominal reevaluation process of a material they thought was promising for a space application:

> This [material] looks good for this application, but this has no flight history. So here are the things we have to do to evaluate it. And sometimes that informs, "well, it's flammable, can we add flame retardants to it? Can the material developer tweak the formulation somehow to meet our needs?" So, it kind of starts that interchange in some way. [3D80]

Radiation SMEs revisited the radiation requirements for feedstocks in the Construction competition. Recall that a material's ability to absorb and withstand the radiation environment on Mars is crucial to providing a safe habitat for the crew. There were initial conversations about including these kinds of requirements, thus asking solvers to provide these analyses [3D6, 3D11, 3D92]. But despite its importance, SMEs decided not to define the radiative environment in the rules. As such, they did not require solvers to take these into account in their solutions[38] [3D92, 3D93, 2018-03-29]. SMEs believed that that teams were "already doing a lot" [3D226], and that this would be too limiting [3D11]. Additionally, the uncertainty did not need to (only) be addressed by the materials: the specific shape and geometry of the habitat could take this into account [3D6, 3D92, 3D93], and the printed structure could be modified to reduce the radiation flux (through, e.g., inflatables or coatings) [3D11]. The material's ability to withstand radiation did not need to be solved in the challenge: like the other material safety criteria, Quinn stated that if a material "was actually going to be infused in the mission, [radiation testing] would be something that NASA and the [material] partner would do together to fly it" [3D93].

6.3.3 Printer Form Factor

Lastly, SMEs maintained their stance against printer designs that used a powder bed. Their reason stayed the same: they wanted to "discourage use of powder-based system[s]" because of the dangers it would pose, both in a microgravity environment [3D92, see also 3D89] and also at the Caterpillar facility where the final round was held [3D226]. In this case, SMEs assigned points to the suitability of the solvers' printers to the space environment—the more suitable the SMEs judged that the systems were to the Martian surface, the higher number of points they would get. In total, SMEs dedicated up to 1% of total points available for level 1 to the printer's suitability for a microgravity environment[39] [3D76].

6.3.4 Outcomes of the Construction Competition

The Construction Competition was another big success. While the participation in this competition was equally as low as Phase 2, the solutions presented SMEs with important insights into the printing processes for different materials. Like the Virtual Construction Competition, SMEs awarded the total prize pot ($1,120M) at each level of this competi-

[38] Note that, like in Phase 2, the material scoring table's preference for polymer binders also partly reflected their utility to protect against radiation [3D11].

[39] The printer's footprint and size were scored together with the microgravity suitability requirement.

tion—the winners took home $55k, $105k, and $500k, for levels 1 through 3, respectively. NASA teams experimented on feedstocks from two teams, further characterizing their in-space performance. And teams from the Construction Competition formed partnerships with NASA teams to design, test, and use additive construction systems for NASA's aims. These partnerships were, collectively, valued in the millions of dollars.

Reflections on Participation Like the Structural Member Competition, participation in this hardware-intensive competition was relatively low. This time, seven teams submitted an entry across the competition's three levels, with only two reaching the final head-to-head [3D127]. Once again, all seven teams stemmed from industry or academia, three and four teams, respectively. Not one non-affiliated team managed to submit a solution. The cause of the low turnout was likely the cost and effort of creating a viable solution yet again. In a survey of participants, several respondents who did not finish their Phase 3 solutions blamed a lack of resources or the amount of work for their lack of progress [3D98]. For example, when asked why they did not complete the phase, one participant responded, "Budgetary constraints in development" [3D98]. Similarly, teams communicated their concerns about the costs of participating, specifically in the final level. As Quinn described: "And [the final level] was something that we got pushback on, even from some of the teams. Saying 'it's really expensive, it's really cumbersome for me to come and afford all this to a head-to-head event'" [3D101].

Similarly, few teams had space industry experience before participating in the Construction Competition [3D55, 3D56, 3D216]. Instead, they came from architecture, civil engineering, and additive manufacturing backgrounds [3D164, 3D165, 3D217, 3D218, 3D219]. However, some teams had participated in previous phases, and by this point in the competition, had started to gain a foothold in the space industry: designing similar systems, establishing a presence, as well as winning other contracts in this industry [3D99, 3D133, CCP71, P3]. NASA personnel observing the 3DPH Challenge expressed their surprise at the evolution of some of the teams: "Those people in Phase 1, I would never have thought [they] would get to Phase 3" [3D100].

Reflections on Solutions

Solvers' materials While SMEs accepted that the rules surrounding materials needed to be relaxed to increase participation, not all were happy with this change. In the Construction Competition, solvers were more able to explore material families and combinations within their capabilities, resources, and goals [3D101]. But some SMEs, like Quinn, felt that the (newly expanded) allowable tradespace for Phase 3 gave solvers too much leeway. In their view, solvers explored materials that were not "in the spirit of the rules" [3D101]. The hydraulic cement concretes "were extremely difficult to deal with. They're very messy," as Ash described [3D94]. In short, they were not feasible for planetary uses. Ash continued their thoughts on how they felt about this change:

> Some of these Portland cements concretes are not realistic for space. We don't have the material, the water, and it's a vacuum. So, I was pushing more for Mars realism. . . . The price we paid [when we made the changes in the rules] was that we got something that was not as good for space but pretty good for Earth. So that's the price you pay for giving [the participants] freedom. You might not get exactly what you want. [3D103]

Despite the relaxation, the solvers still produced feedstocks that SMEs thought were "novel and innovative" [3D73]. First, the winner of the final level—AI Spacefactory—developed a polymer-based feedstock where the binder, polylactic acid (PLA) plastic, could be produced on Mars. It would tie into existing NASA's synthetic biology programs to do so [3D162] and further reduce planetary construction costs [3D226]. Additional advantages included radiation shielding (per 5.2.3), low changes in volume based on temperature (per 6.3.2), and low hardening time [3D73]. Along with the PETG binder from Phase 2, SMEs touted it publicly as one of the polymer blends "with potential applicability" for their vision of in-space manufacturing [3D140].

Finally, two teams printed with concretes relevant to planetary environments but had to drop out of the competition. One team used a magnesium oxide cement as a feedstock, a readily available compound in lunar and Martian regolith [3D65, 3D73]. MSFC SMEs had tried this in their ACME project but were not successful. Per one of its leads[40]: "We started using [magnesium oxide cement] in the ACME project. And it's horrible. Our formulation of that is absolutely awful. But that doesn't mean that another [company] or somebody couldn't make a better formulation with the same materials." Ultimately, difficulties with implementing autonomy in their printing system and a lack of resources made it difficult for the team to continue [3D216].

Another team based their concrete on sulfur. SMEs were interested in this material for its potential as a binder—the ACME project had also investigated it previously [3D65, 3D160]. Despite its applicability to planetary context, however, the logistics of the competition were too big a hurdle to overcome. It came down to safety: sulfur needs to be heated to flow as a binder and releases toxic fumes in the process [3D89, 3D101]. Per Blake: "Well, it's really problematic from a safety standpoint, especially when you have large crowds. You couldn't have them in the open area there at Peoria" [3D160]. In collaboration with Caterpillar, SMEs tried to work out a strategy to keep onlookers safe: confining the printer to a plastic tent with ventilation to the outside was one serious consideration; printing via video link was another [2019-03-21, 3D95, 3D160]. But in the end, the team decided not to participate in the final level [2019-03-28, 2019-04-03].

In both cases, SMEs had hoped these teams could have continued their development to learn from their designs. Finley "[was] hoping that Northwestern would come with their sulfur concrete, or Colorado School of Mines with their magnesium oxide…" [3D82]. In our interview, Finley described the kinds of questions they would ask these teams, ranging from their feedstock design, feedstock handling just before printing, to printing and control processes [3D95]. Relatedly, several SMEs lamented that these teams had dropped out.

[40]Reference withheld to maintain interviewee anonymity.

Finley acknowledged that "it would have been a logistics nightmare [to accommodate them] down there. But it would have been really cool." [3D95]. Likewise, Quinn commented that allowing teams to participate from their home location—something that was initially considered—could have kept these teams in the competition [3D226].

Solvers' robotic architectures SMEs were happy to see the range of printer architectures the solvers designed. In particular, SMEs were impressed by the combinations of printers and machinery to move it around the printed object [3D73, 3D160]. Blake was "really intrigued and tickled to see the range of mobility system designs that were a function of the selected architecture. It was pretty cool" [3D89]. SMEs praised the demonstrations of these printing architectures [3D109]: they showed that previously unprintable structures might not be. Quinn described the demonstrations made by solvers as follows:

> I think, from the perspective of the actual manufacturing equipment, it really provided NASA with a good calibration of what the state-of-the-art is with these technologies, and how we can push that a little bit in terms of being able to build larger, have higher material deposition rates. [3D80]

Solution infusion into NASA projects After Phase 3, SMEs characterized two feedstocks from the Construction Competition. Samples of both the winner's and the runner-up's feedstocks will fly or have flown on-orbit. AI Spacefactory flew their PLA and basalt fiber feedstock on a United States Air Force experiment called Materials Exposure and Technology Innovation in Space (METIS) [3D80, 3D151]. PSU will fly their hydraulic-cement feedstock on Materials International Space Station Experiment (MISSE) [3D134]. In both experiments, the samples are exposed to the space environment. Here, NASA can "gain valuable data about how the materials hold up in the environment in which they will have to operate," per the co-investigator and principal investigator those payloads [3D168, see also 3D80]. And Quinn thought further characterizing these feedstocks on-orbit was another of the "really good outcomes" [3D80].

Partnerships Resulting from the Construction Competition

Developing printing infrastructure for the moon The partnerships between NASA and the 3DPH Challenge teams described in 6.2.3 included a significant hardware component and the architectural work. SMEs from both MSFC and KSC relied on the solver teams to develop printer architectures for the lunar surface. In the MMPACT project, MSFC also partnered with ICON—a terrestrial additive construction firm that collaborated with the Colorado School of Mines in the Construction Competition [3D186, 3D215]. Per their stated vision, ICON's task would be to develop and test new feedstocks using lunar soil simulants [3D172]. They would then use these insights to develop and "increase the technology readiness level" of key elements of the lunar printer [3D159, see also 3D172]. While ICON's participation in the 3DPH Challenge certainly raised its visibility, its maturity in its processes won over the additive construction SMEs. As one of them described[41]:

> When we were looking for a printing company counterpart for the MMPACT project, [we] listed every company in the US that was doing either printer development or structure development, and immediately ICON rose to the top. So we went and talked to them. ... I wanted somebody with a demonstrated process. I wanted somebody who wasn't just building and selling printers but was actually printing. So I knew that they understood the actual printing operations and the kinds of things that you can run into.

The REACT project has similar components. The participant team, AI Spacefactory, will work with the KSC SMEs to develop a material "that mimics lunar regolith, or dirt," per their press releases [3D154, see also 3D155]. Likewise, they will use their insights to design and test printer elements that can support this kind of material—in this case, an extruder [3D185]. In contrast to MMPACT, however, this partnership placed a stronger emphasis on testing in equivalent conditions. Specifically, the KSC SMEs described how part of their role was to convey the specifics of the lunar environment, provide these conditions in a test chamber, and help the AI Spacefactory team tailor their design to work in these conditions

[41] Reference withheld to maintain interviewee anonymity.

[3D154, 3D155, 3D185]. Per an SME on this partnership[42]:

> So, one of the responsibilities on our end is to convey what the lunar environmental conditions are so that they can tailor the design of the material and of the structure itself in a way that will be functional in the lunar conditions. ... So, we provide that insight over to them and help them modify and adjust their system so that they can perform in that environment.

Printing an analog habitat Early on, the Design Competition's rules envisioned a 3D printed habitat analog where a crew could train for their stay on Mars. About five years later, this would become a reality. JSC team was planning NASA's first long-duration habitat simulation, where a crew of (simulated) astronauts would live inside a simile of a habitat for a year [3D160, 3D223]. Crew Health and Performance Exploration Analog (CHAPEA) would track their food intake and how they interacted with the space, among other factors [3D224]. Under budget and schedule pressures, the CHAPEA team investigated different options for a space that could suit their needs, including building a purpose-built one.

Here, the CHAPEA team included additive construction (of a dedicated habitat) as one of those options. The team consulted with the 3DPH Challenge team to better understand (if and) how this method could work for their needs [3D160]. These conversations were crucial in helping this method gain traction as a viable option—the CHAPEA team had not set out to use this construction method. Per a CHAPEA team member who was a part of the discussions between their team and the CCP:

> So, in talking with [the CCP lead] and her team, the first thing I realized was that this was a viable option. Because I didn't know. You can go online and read about things, but having that connection with her team made me realize that "ok, this is something realistic and feasible for us to do." [3D221]

Additive construction was the most attractive option for this project [3D221]. First, the timeframe to additively construct the required building fitted within CHAPEA's schedule. Second, ICON presented the cheaper bid—attributed to not developing the hardware needed to print the habitat and their long(er) experience in printing this size of the structure. Third,

[42] Reference withheld to maintain interviewee anonymity.

this option had the added benefit of providing another demonstration of new technology. Per the CHAPEA team member, “it was the only one that had the benefit of maturing— possibly helping to mature technology that NASA was looking for outside of Earth” [3D221]. So, NASA launched a procurement to print their analog habitat [3D157].

Additionally, one important risk would give a 3DPH Challenge participant an advantage in their bid. This structure would need to support the crew over an extended period, and their safety was paramount [3D221]. Additive construction is a new technology, and teams were still developing their printing systems while bidding on the project. In contrast, ICON had already successfully navigated their city’s building codes (Austin, TX) and had printed homes that people currently were living in [3D160]. To the CHAPEA team, this proxy for safety weighed more than the characteristics that interested the formulation team. Per the CHAPEA team member again:

> From my perspective, the functionality of how each of these companies print, or the specifics of their printer, is less important for me being able to say, “I have evidence that says if I put four people in this structure, they’re going to be safe.” [3D221]

References

Table 1: Documents referenced in the “Formulating the 3DPH Challenge” Case Narrative

Reference	Date created	Description
3D1	Jul 25 2013	Agreement between NASA and DOE concerning NNMI
3D2	Mar 9 2015	First draft of 3DPH Challenge rules
3D3	Apr 3 2015	Whiteboard of Brainstorming session (Design Challenge goals)
3D4	Apr 3 2015	Whiteboard of Brainstorming session (Design Challenge rules)
3D6	Mar 30 2015	Second draft of 3DPH Challenge rules
3D7	Apr 8 2015	Revision of 3DPH Design Challenge rules
3D8	Apr 14 2015	Revision of 3DPH Design Challenge rules
3D10	May 1 2015	Revision of 3DPH Design Challenge rules
3D11	Aug 28 2017	Interview with “Riley”

3D12	Jul 25 2015	First draft of 3DPH Challenge “Level 2” rules (printing the full habitat on site)
3D13	May 7 2015	Executive summary of the Design Challenge
3D16	May 15 2015	Notice (SpaceNews) describing Design Challenge launch
3D17	May 16 2015	Final version of 3DPH Design Challenge rules
3D20	July 13 2015	First draft of 3DPH Structural Member Challenge rules (with CCP team commentary)
3D21	Apr 3 2015	Whiteboard of Brainstorming session for Structural Member Challenge
3D22	Apr 3 2015	Whiteboard of Brainstorming session for “Level 2” (printing the full habitat on site)
3D23	Apr 14 2017	Final Structural Member Challenge rules
3D24	Jul 09 2018	Questions to “Finley” via email
3D25	Jul 13 2018	Questions to “Finley” via email
3D26	Aug 21 2015	Team’s descriptions of designs
3D27	Aug 24 2017	Interview with CC3
3D28	Aug 24 2017	Interview with “Ash”
3D29	Jul 16 2018	Questions to CC16 via email
3D30	Jun 26 2017	Questions to “Riley” via email
3D31	Sep 23 2016	EMPC Presentation and request for ATP for 3DPH Challenge Phase 2
3D32	Apr 4 2018	3DPH Phase 3 Webinar on Virtual Construction and BIM
3D33	N/A	Completed Technology Project: progress by the ACME project under GCD (summary)
3D34	Nov 7 2017	ACME 3D Printing Structures with ISRU-Presentation
3D35	Aug 7 2015	Brief factsheet on GCD grant for ACME
3D36	Aug 24 2017	Interview with “Quinn”
3D37	N/A	Slide describing high-level requirements for Ice Home project
3D38	Aug 17 2016	Ice Home CONOPS baseline
3D39	Dec 21 2017	Ice Home CONOPS revision 1.20
3D43	Jul 2016	Mars Ice House conference paper–Conference on Environmental Systems, ICES-2016-222
3D48	2018	Penn State Tech Summary: 3D Printing Geopolymer Structures Having a Lower Ecological Footprint ID# 2017-4699
3D55	Jul 1 2019	SDSU XHAB results summary: Development and Mechanical Properties of Basalt Fiber-Journal paper in Composites Science
3D56	May 31 2018	NASA Selects University Teams to Develop System Prototypes for Deep Space-Press release
3D63	Jul 21 2017	Additive Construction: Using In?Situ Resources on Planetary Surfaces-Presentation
3D65	Nov 1 2018	The Disruptive Technology That is Additive Construction: System Development Lessons Learned for Terrestrial and Planetary Applications-AIAA Space 2018
3D69	Oct 2018	NASA Centennial Challenge: Three Dimensional (3D) Printed Habitat, Phase 3-IAC 2018, IAC-18-E5.1.5

3D71	Feb 2014	TechPort: 3D Additive Construction with Regolith for Surface Systems-Technology Factsheet (CIF)
3D72	Apr 11 2016	NASA Centennial Challenge: Three Dimensional (3D) Printed Habitat-ASCE Earth and Space Conference 2016
3D73	Mid year 2019	Centennial Challenges Program 3D Printed Habitat Challenge Mid-Year report (FY2019)
3D76	Jun 27 2018	Final Phase 3 (Virtual Construction and Construction) rules
3D79	May 3 2019	Interview with "Quinn"
3D80	Oct 4 2019	Interview with "Quinn"
3D81	Apr 30 2019	Interview with "Quinn"
3D82	Apr 30 2019	Interview with "Finley"
3D87	May 3 2019	Interview with "Stevie"
3D88	Apr 12 2019	Interview with "Billie"
3D89	Apr 29 2019	Interview with "Blake"
3D90	May 31 2017	UAF Lawlor wins NASA prize-Press release
3D91	Jun 4 2019	Questions to "Quinn" via email
3D92	Mar 17 2020	Excerpts from relevant email traffic between SMEs on judging team
3D93	Dec 4 2019	Interview with "Quinn"
3D94	Oct 15 2019	Interview with "Ash"
3D95	Oct 25 2019	Interview with "Finley"
3D96	May 2 2019	Interview with "Harper"
3D97	May 16 2015	Reference page included with final draft of 3DPH Design Challenge rules
3D98	Oct 10 2019	CCP survey of 3DPH participants
3D99	Sep 2018	NASA Centennial Challenges Program Update-AIAA Space 2018
3D100	April 3 2019	Interview with NASA SMEs
3D101	Mar 16 2020	Interview with "Quinn"
3D102	Feb 20 2020	Interview with "Finley"
3D103	Mar 10 2020	Interview with "Ash"
3D104	Aug 24 2017	Interview with CC2
3D105	Mar 12 2020	Interview with "Harper"
3D106	April 29 2020	Interview with "Billie"
3D107	Sep 05 2018	Midterm Webinar (and review of Phase 3 to date)
3D108	Oct 25 2017	EMPC Presentation and request for ATP for 3DPH Challenge Phase 3
3D109	Feb 20 2020	Additive Manufacturing at NASA overview
3D110	July 10 2015	First draft of Structural Member Challenge rules
3D112	July 13 2017	FAQ document for Structural Member Challenge
3D115	Nov 14 2019	In-Situ Resource Utilization: Robotics and 3D printing as the Picks and Shovels of the 21st Century-Presentation
3D116	May 8 2019	Interview with CC25
3D117	May 16 2015	3DPH Challenge promo at Maker Faire 2015-YouTube video
3D118	May 16 2015	Design Challenge launch at Maker Faire 2015-YouTube video

3D119	Oct 12 2015	Design Challenge promo-YouTube video
3D120	Dec 19 2017	Informational Webinar (for Phase 3)
3D121	Apr 4 2018	3DPH Phase 3 Webinar on Virtual Construction and BIM (Transcript)
3D122	Nov 16 2016	Informational Webinar (for Phase 2)
3D124	Jun 13 2017	Mars Ice Home description-Presentation
3D125	Jun 23 2017	Interview with CC26
3D127	Mar 20 2020	CCP summary of participation and awards in all 3DPH phases
3D130	May 16 2018	Zero Launch Mass Three Dimensional Print Head-ASCE Earth and Space Conference 2018
3D133	N/A	AI Spacefactory press coverage
3D134	Sep 23 2020	Interview with “Quinn”
3D135	Oct 2 2020	NASA’s Project Olympus-Press release
3D137	Jun 21 2018	Robotics in Construction (NASA Swampworks)-Presentation
3D140	Nov 21 2019	The Proving Ground: Using Low Earth Orbit as a Test Bed for Manufacturing Technology Development-Presentation at 1st International Conference on 3D Printing and Transportation 2019
3D147	May 4 2019	Interview with CC24
3D150	May 1 2019	Interview with CC26
3D151	Nov 11 2020	Questions to “Blake” via email
3D154	Nov 9 2020	New NASA Partnerships to Mature Commercial Space Technologies, Capabilities-Press release
3D155	Nov 10 2020	Kennedy to Partner with Previous NASA Challenge Winner for Lunar Research-Press release
3D156	Jul 2020	3D-Printing Lunar and Martian Habitats and the Potential Applications for Additive Construction-International Conference on Environmental Systems 2020
3D157	Aug 28 2020	CHAPEA sole source contract description
3D159	Oct 1 2020	NASA looks to advance 3D Printing Construction Systems for the Moon and Mars-Press release
3D160	Sep 9 2020	Interview with “Blake”
3D161	Mar 18 2019	FAQ document for 3DPH Phase 3
3D162	Mar 29 2018	ISRU Construction & Excavation of Regolith-Presentation
3D163	Oct 2015	Additive Construction using Basalt Regolith Fines (Additive construction at Swampworks)-ASCE Earth and Space Conference 2015
3D164	May 2 2019	Interview with 3DPH participant 3D13SB1
3D165	May 2 2019	Interview with 3DPH participant 3D14SB1
3D166	Oct 1 2018	Technical Risk Reduction for the Mars Ice Home Habitat Concept-IAC 2018, IAC-18-F1.2.3
3D167	Apr 24 2019	Microgravity Effect on Microstructural Development of Tricalcium Silicate (C3S) Paste-Journal article in Frontiers in Materials
3D168	May 6 2015	NASA Test Materials to Fly on Air Force Space Plane-Press release

3D169	Jan 23 2019	Concrete in Space Investigating cement solidification in a microgravity environment-Press release
3D171	2015	Completed technology project: Ice dome, Center Innovation Fund: LaRC CIF-Summary
3D172	Oct 7 2020	NASA Looks to Advance 3D Printing Construction Systems for Moon, Mars-Press release (Marshall Star)
3D174	Apr 23 2019	Designing Sustainable Homes on Mars and Earth-Press release (Penn State)
3D180	Sep 25 2017	Additive Construction with Mobile Emplacement (ACME)-IAC 2017, IAC-17-D3.2.1
3D181	Feb 14 2014	Fanuc arm arriving at Swamp Works for 3D printing of buildings-Twitter
3D185	Feb 24 2021	Interview with “Jude”
3D186	Oct 1 2020	NASA, BIG, SEArch+, and ICON team up to develop a lunar city-Press release
3D187	Aug 25 2017	Interview with CC5
3D188	May 9 2016	Interview with 3DPH participant 3D3HB1
3D189	Sep 2018	NASA’s Centennial Challenge for 3D-Printed Habitat: Phase II Outcomes and Phase III Competition Overview-AIAA Space 2018
3D190	Feb 20 2018	Current NASA Plans For Mars In Situ Resource Utilization-Presentation
3D191	Jul 31 2020	State of ISRU Construction at NASA-Presentation
3D192	Aug 24 2015	Space Environment & Planetary Civil Engineering Basics-Presentation
3D193	Apr 20 2021	Descriptions of benefits of the 3DPH Challenge via email
3D194	2015	How to 3D-print a habitat on Mars-Press release (Team Lavahive)
3D195	May 24 2016	Interview with 3DPH participant 3D6LB1
3D196	May 3 2016	Interview with 3DPH participant 3D1SB1
3D197	May 13 2016	Interview with 3DPH participant 3D5HB1
3D198	May 17 2016	Interview with 3DPH participant 3D4CS1
3D200	Nov 2019	LOD Specification Part 1 and Commentary (BIM Forum)
3D201	Sep 23 2019	Use of LOD in Mars Habitat Design Competition-Presentation
3D202	May 3 2019	Interview with 3DPH participant 3D15SB1
3D203	May 3 2019	Interview with 3DPH participant 3D17HB1
3D204	Apr 2017	Hypervelocity impact testing of materials for additive construction: Applications on Earth, the Moon, and Mars-14th Hypervelocity Impact Symposium 2017
3D205	Jan 21 2009	President’s Memorandum on Transparency and Open Government - Interagency Collaboration-Memo
3D206	Sep 30 2015	Addressing Societal and Scientific Challenges through Citizen Science and Crowdsourcing-Memo
3D207	May 19 2017	Interview with 3DPH participant 3D7HB1
3D208	Aug 24 2017	Interview with 3DPH participant 3D10U1
3D209	Aug 25 2017	Interview with 3DPH participant 3D6L4

3D210	Aug 25 2017	Interview with 3DPH participant 3D12SB2
3D212	Nov 11 2020	CCP calculation of 3DPH Challenge ROI
3D213	Jun 30 2021	House Appropriation Committee ACOs for NASA
3D214	Sep 23 2021	Questions for "Jude" via email
3D215	Nov 3 2021	Overview of NASA's Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT)-ASCEND Conference 2021
3D216	May 3 2019	Interview with 3DPH team 3D16
3D217	Sep 4 2018	Innovations in 3D Printing: Nathan Fuller, Form Forge-YouTube video
3D218	Aug 25 2017	Interview with 3DPH participant 3D11U2
3D219	2018	Martian 3Design Team (NWU) team roster
3D221	Feb 3 2021	Interview with CC30
3D223	Aug 5 2021	NASA CHAPEA mission description
3D224	Aug 6 2021	NASA is Recruiting for Yearlong Simulated Mars Mission-Press release
3D225	Aug 24 2021	Interview with "Billie"
3D226	Jan 18 2022	Quinn's written comments on an earlier version of this document
3D227	Feb 11 2022	Ash's written comments on an earlier version of this document
LE1	Feb 20 2020	Researcher notes at Lunar Excavation Challenge Workshop
LE3	Feb 20 2020	Lunar Excavation Challenge Workshop: all slides (briefing portions)
P3	Mar 1 2018	CCP Annual Report 2017
P5	Feb 22 2016	CCP Team presentation to Program Management Council
P13	Aug 17 2015	Outcome-driven open innovation at NASA-Journal article in Space Policy
P17	Feb 6 2014	The Road to Realizing In-space Manufacturing-Presentation
P18	Oct 24 2019	Interview with CC2
P19	Dec 7 2015	Researcher notes on CCP research kickoff meeting
P23	Nov 2010	DRAFT Human Exploration Destination Systems Roadmap, Technology Area 07

Table 2: Formulation Team Minutes of Meeting referenced in the "Formulating the 3DPH Challenge" Case Narrative

Weekly minutes: "3D Habitat Centennial Challenge—Rules & Execution Team"
2017-02-02, 2017-03-02, 2017-05-04, 2017-05-18, 2017-06-15, 2017-06-22, 2017-07-13, 2017-07-14, 2017-07-20, 2017-07-27, 2017-08-03, 2017-08-31, 2017-10-26, 2017-12-20; 2018-01-04, 2018-01-11, 2018-02-08, 2018-02-15, 2018-03-22, 2018-03-29, 2018-04-11, 2018-05-31, 2018-07-12, 2018-07-17, 2018-07-19, 2018-08-02, 2018-11-15, 2018-12-13; 2019-01-31, 2019-03-21, 2019-03-28, 2019-04-03

Table 3: CCP Minutes of Meeting referenced in the "Formulating the 3DPH Challenge" Case Narrative

Weekly minutes: "Centennial Challenges Program (CCP) Weekly Status"
CCP7, CCP10, CCP15, CCP20, CCP49, CCP71, CCP103, CCP124, CCP126, CCP132, CCP144, CCP147, CCP152, CCP154, CCP167