Additive Manufacturing

— FOR DEFENSE AND GOVERNMENT —

Washington DC – May 13-14, 2015

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The Promise and Realities of Additive Manufacturing (3D printing) in Space

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Presented at

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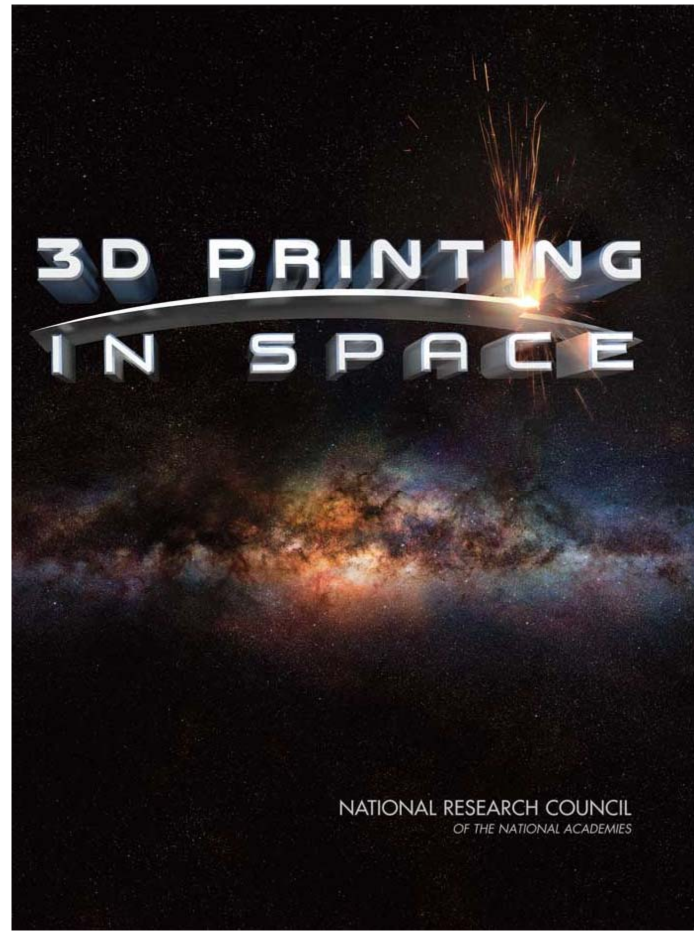
Overview

- Background of the study
  - Promise of additive manufacturing in space
  - Reality
  - Committee overall findings and recommendations

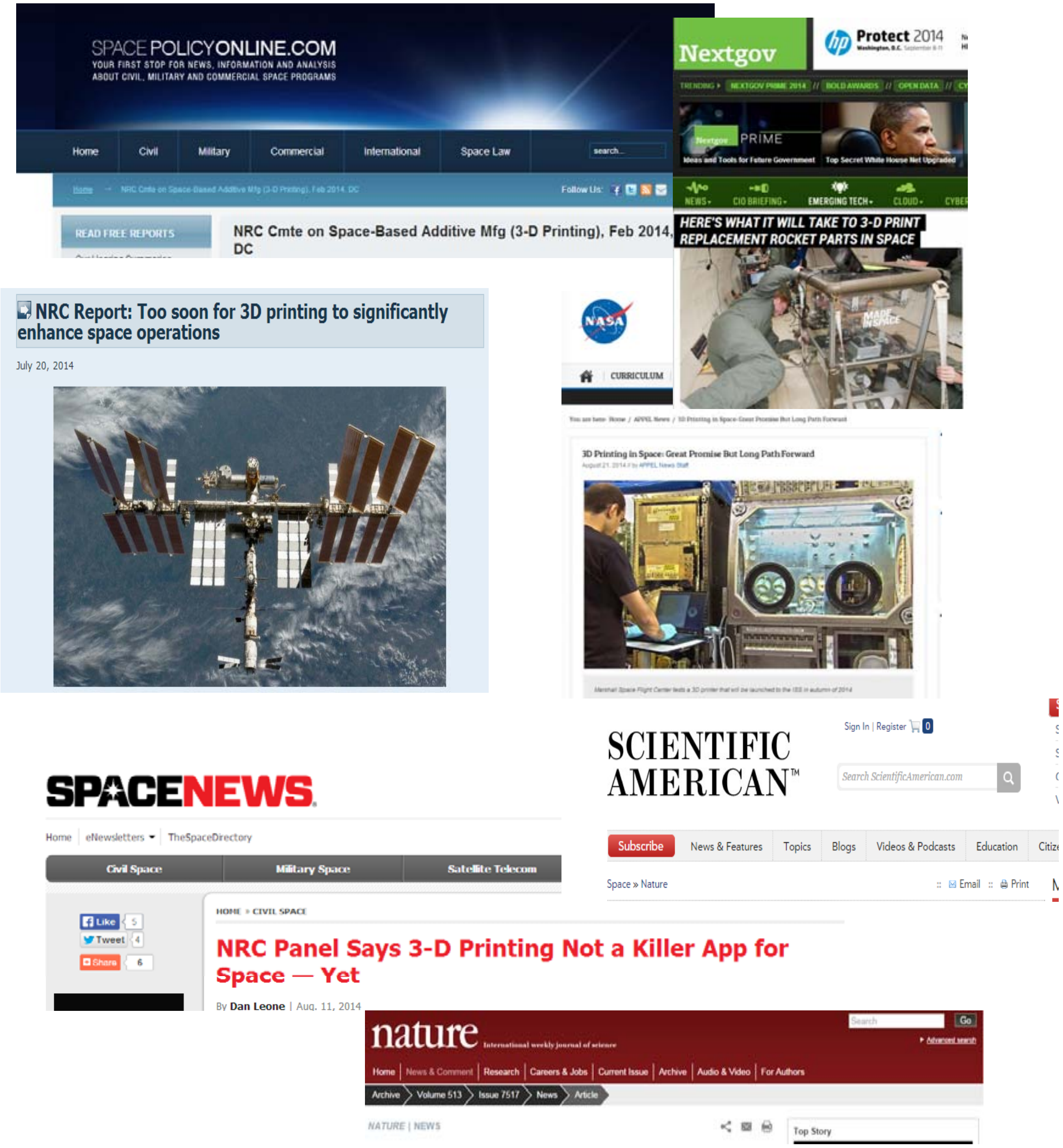
BACKGROUND

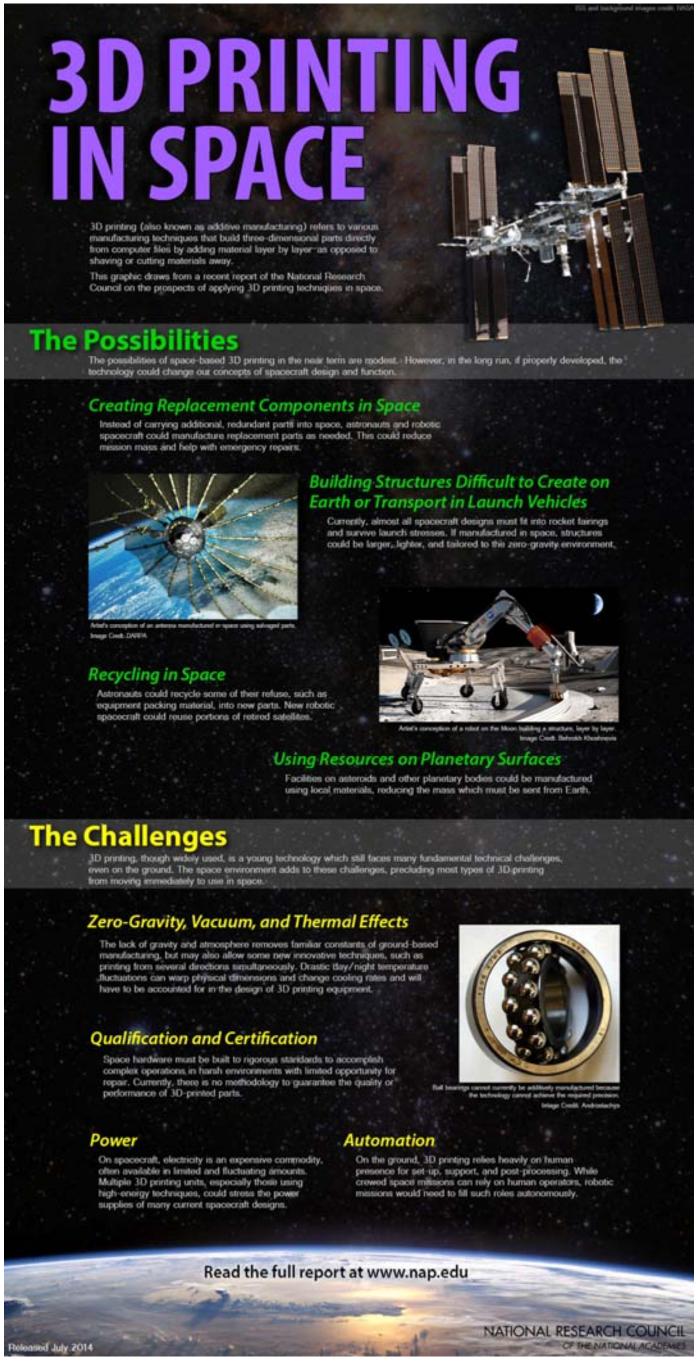
National Research Council Study

- Air Force Space Command, the Air Force Research Laboratory Space Vehicles Directorate and the NASA Science and Technology Mission Directorate, requested the US National Research Council (NRC) to
  - Evaluate the feasibility of the concept of space-based additive manufacturing of space hardware
  - Identify the science and technology gaps
  - Assess the implications of a space-based additive manufacturing capability



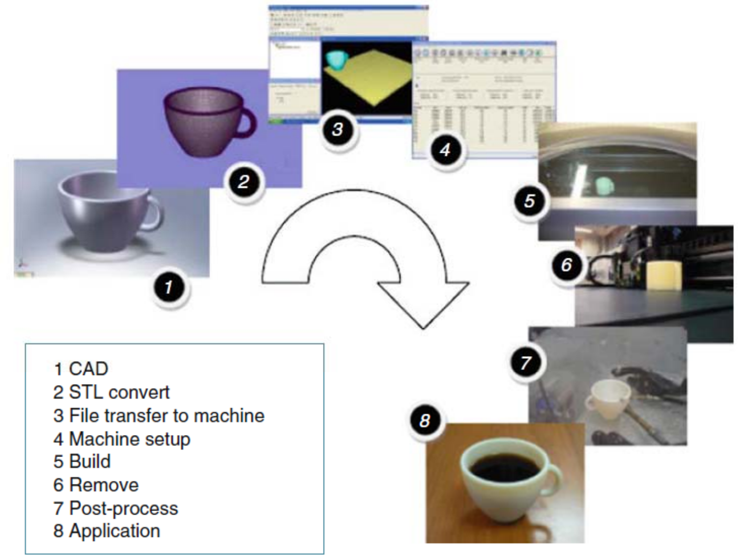
- Wide Media Coverage

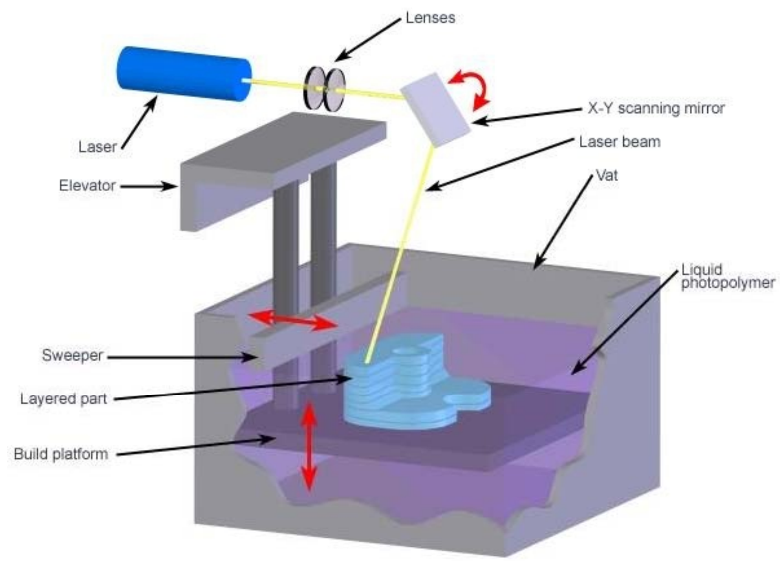




What is Additive Manufacturing?

- Additive manufacturing is the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."
- Technology has existed since the 1980s - primary change is that machines have become cheaper and range of uses has expanded
- Almost 50 manufacturers worldwide producing and selling industrial-grade AM machines - market $4.1 billion in 2014, from $3 billion in 2013 (growing 76% from previous year) - expected to be $21 billion by 2020
- AM expected to become a $200 b industry

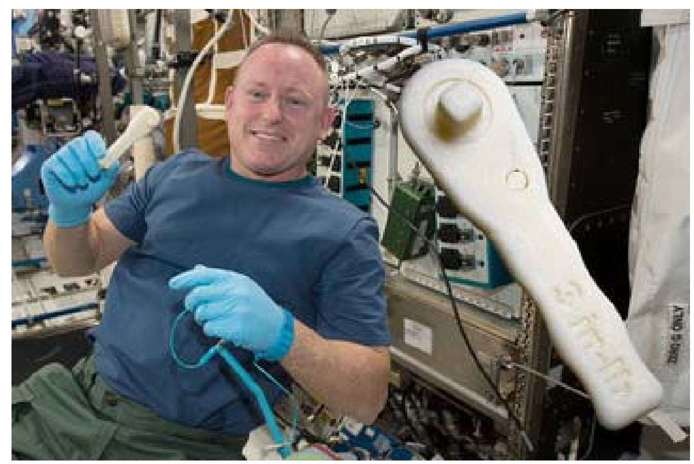




Additive Manufacturing FOR Space vs IN Space

- SpaceX's Super Draco engine includes a 3D printed combustion chamber made of Inconel created by direct metal laser sintering
- 3D printing happened terrestrially

- 3D printer on the ISS made a total of 14 test objects *on the ISS*, one of which, a ratcheting socket wrench, made history as the first-ever tool emailed to space
- 3D printing happened in Space



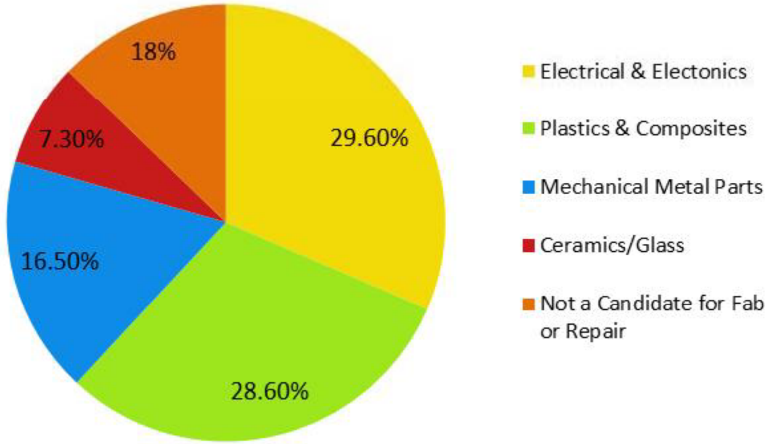
Committee focus was in-space additive manufacturing

THE PROMISE

Manufacturing Components

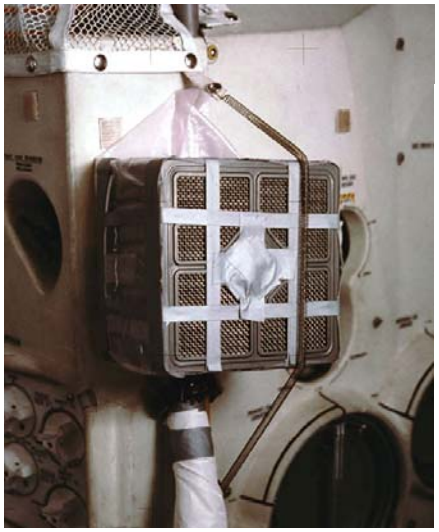
- Instead of carrying additional, redundant components for the ISS, parts can be manufactured as needed
- Replace outdated/broken hardware on satellites
- Reduce storage, recall, wait-time on ISS, extend satellite life - reduce frequency and cost of launch
- NASA funded *Made in Space* to explore the printing of parts on the ISS; ESA/Italy has similar plans

SOURCE: NASA

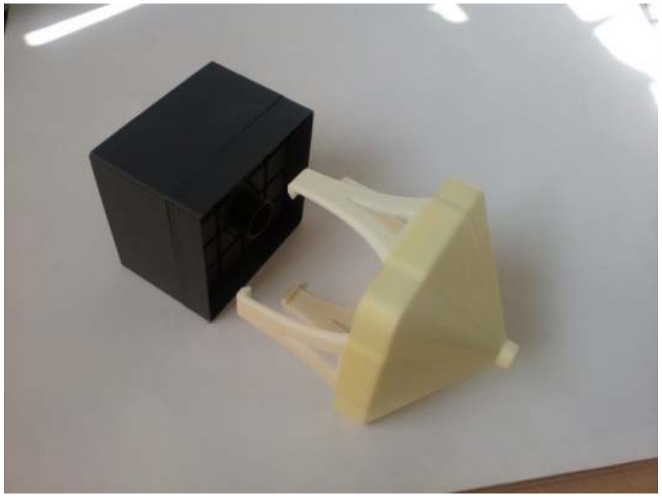


Manufacturing Components – Familiar Story with a Twist

- In 1970, the Apollo 13 astronauts had to have a lot of help from Houston to make an adapter to filter CO_2 in the Lunar Module – a few harrowing days for all



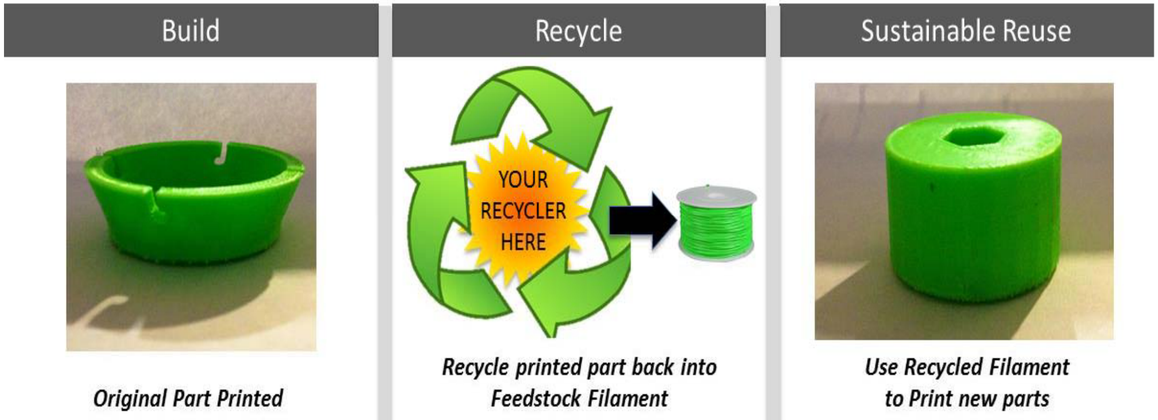
- In 2013, an engineer from *Made In Space* spent ONE hour designing an adapter for the lithium hydroxide canister and was able to print it
 and demonstrate its operation by
the end of the day
  - 3D printer on such a mission would probably have used way more power than they had available



SOURCE: NASA

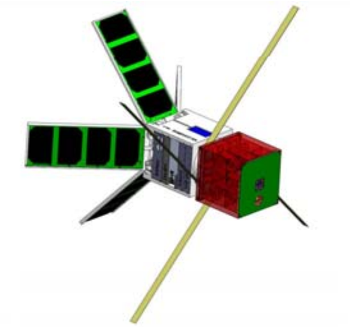
Recycling

- Currently, astronauts pack trash into robotic spacecraft such as the Russian Progress and the Orbital Sciences' Cygnus for disposal.
- The spacecraft are detached from the station and burn up in the atmosphere. But before that happens, astronauts spend a considerable amount of time moving the trash simply to get it out of the way.
- Additively manufacturing using recycled materials might ease this logistics and operations problem.
- Both the component creation and recycling scenarios offer the ability to launch feedstock instead of delicate hardware or useless packaging



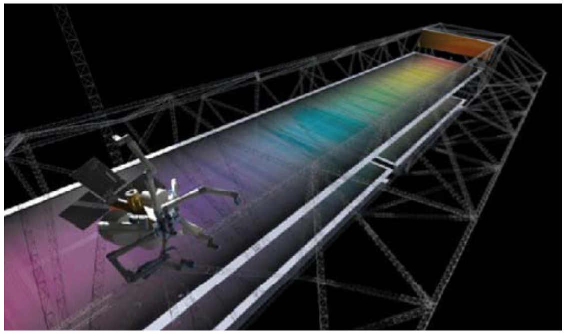
Creating Sensors or Entire Satellites in Space

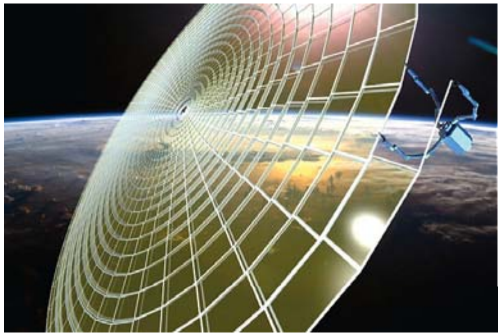
- Additive manufacturing in space could—autonomously or with human support—create not just components but an entire “spacecraft” in space
- A single-function spacecraft is feasible on a shorter timeline than a multiple function spacecraft that is radiation and nuclear hardened, intended to last multiple years, made of multiple materials, and serves many functions
- Mission needn't be designed ahead of launch - build it when you get there
- NASA Innovative Advanced Concepts (NIAC) supporting research at JPL

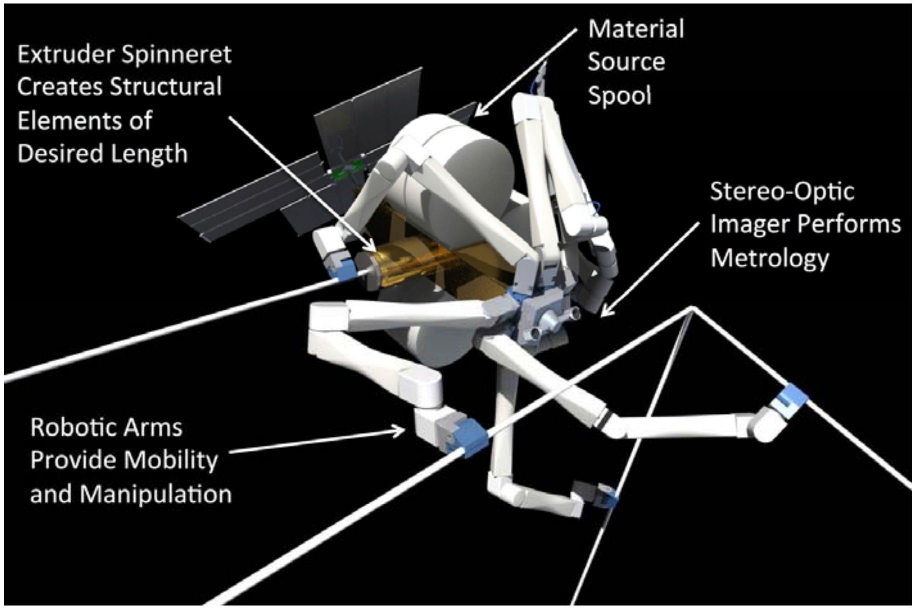


Creating Structures Difficult To Manufacture On Earth Or Launch

- Currently, large components and systems are designed for launch
- Their delicate structures, sizes and shapes are limited by the requirement to stow them within available launch fairings
- Some structures – like gossamer sails, threads, ultra thin mirrors – cannot be a built AT ALL in a gravity environment
- On-orbit construction can enable deployment of systems that need not conform to weight and volumetric constraints posed by launch fairings and shrouds - feedstock needn't be robust to structural stresses related to launch
- NASA Innovative Advanced Concepts (NIAC) and DARPA supporting research

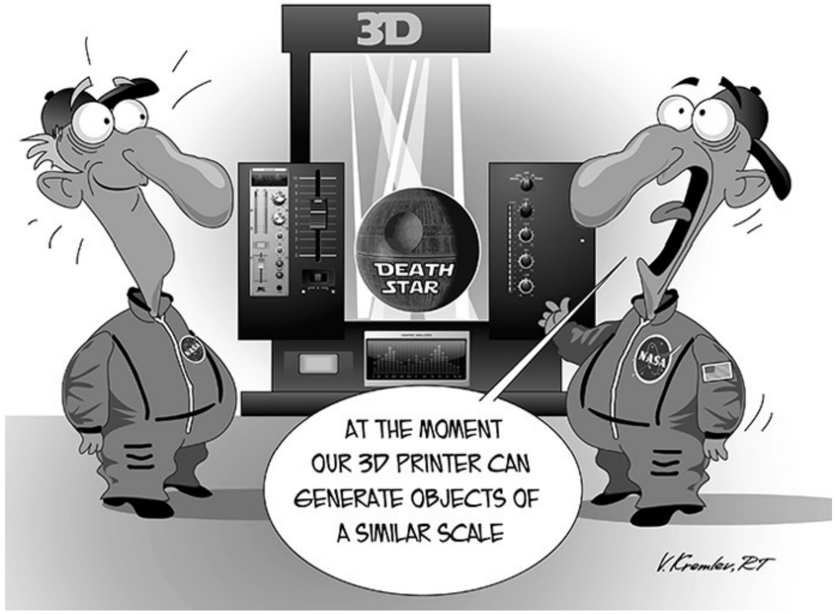






Using Resources on Off-Earth Surfaces

- Lunar regolith could be used to construct pressurized habitats for human shelter, as well as other infrastructure on the Moon
- NASA Innovative Advanced Concepts (NIAC) program exploring technique called contour crafting to build infrastructure on the Moon using simulated lunar regolith.
- The European Space Agency is funding similar research with a technology called D-Shapes to design moon-based habitat.



THE REALITY – CHALLENGES TO ATTAINING VISION

Technology Challenges at Multiple Levels

NRC Report: http://www.nap.edu/download.php?record_id=18871

Terrestrial Challenges

- New materials
- Process modeling
- Precision and resolution
- Construction time
- Design tools and software

Infrastructure Related Challenges

- Manufacturing Platform
- Data and Telemetry
- Power

In-Space Challenges

- *Gravity*
- Vacuum
- *Thermal Environment*
- *Quality, Verification, Validation and Functional Testing*

ISS-specific challenges

- Safety

Free-flyer platforms

- Autonomy

Celestial Surfaces

- Suitability of *in situ* resources as feedstock

Zero/Micro Gravity

- Reduced or zero gravity environment will not only have an effect on the <u>process parameters and techniques</u>, but potentially an effect on the <u>final mechanical and functional integrity</u> of the finished part
  - Surface tension forces become important determinants of system behavior and processes that rely on the control of fluid or flow conditions will need further research.
  - Floating debris can damage the product and the machine and will have to be controlled.
- Robotic interaction with the additive manufacturing process may be required in the absence of gravity to position and constrain the developing part geometry.

➢ Lack of gravity is not just a constraint or an environmental problem to overcome, opportunity to explore entirely new techniques - lack of gravity might permit a printer to work on the "bottom" and the "top" of an object at the same time.

Thermal Environment

- Thermal effects related to the lack of convection will impact any of the targeted processes
- An externally placed additive manufacturing system operating in Earth orbit will experience similar thermal loads of solar, albedo and Earth infrared during an orbit as would a spacecraft
- Both the operation and performance of the manufacturing system and the dimensional accuracy of the product being produced will be impacted

- However, there are potential solutions, such as shielding the equipment behind a sunshade, as is done for some space-based telescopes

Quality, Verification, Validation and Testing

- Adverse conditions of remoteness and visual impairment due to unique white light conditions have to be taken into account
- Autonomous inspection of the manufacturing process in situ may be required
- Process sensitivity to the space environment which includes microgravity and thermal conditions, will have to be fully characterized to ensure repeatability and thus part quality.
- Because the degree to which these various factors influences additive manufacturing is still being investigated in 1*g*, appropriate measurement and testing will be required beyond the terrestrial testing performed.
- The level and type of validation and verification required will depend heavily on the complexity of the product being produced - approaches designed for qualifying simple parts may not be scalable to an additively manufactured complex system.

SUMMARY FINDINGS AND RECOMMENDATIONS

10 Findings in Five Categories

- **Additive manufacturing in space has great potential.** Space system configurations that are currently dominated by requirements to survive ground manufacturing, assembly, test, transport, and launch could be reexamined as AM capability becomes available, and *additive manufacturing might provide the means to transform space architectures*.
- **However, there are many technological and regulatory hurdles before such as vision could be achieved.**
- **Terrestrial challenges remain unresolved.** Before moving additive manufacturing technology to the space environment, further development in several fundamental areas needs to be complete and well understood. These areas represent barriers to a wider use, even in a ground-based environment, and *preclude additive manufacturing techniques moving immediately to a space-based environment*.
- **Space related challenges magnify terrestrial ones.** The space environment (zero gravity, vacuum) poses additional constraints, and additive manufacturing is even more of a systems engineering and industrial logistics problem compared to additive manufacturing on the ground.
- **Technology not implementable without supporting infrastructure.** Supporting infrastructure and environment which are relatively straightforward and easy considerations on the ground (i.e. rent factory space, connect to the local power grid) are not simple for space - issues such as supply chain logistics, integrated processes, minimal human interaction, and quality control are more pronounced.

15 Recommendations for Air Force and NASA in Five Categories

- **Analysis**. Agencies need to do systems *and* cost benefit analyses (CBA) related to the value of AM in space. The analyses should not focus just on how AM could replace traditional manufacturing but how it can enable entirely new structures and functionalities that were not possible before. A specific area where a CBA would be helpful is in the manufacture of smaller satellites on the ISS.

- **Investment**. Targeted investment is needed in areas such as standardization and certification, and infrastructure. The investment should be strategic, and use workshops and other information-sharing forums to develop roadmaps with short and long-term targets.

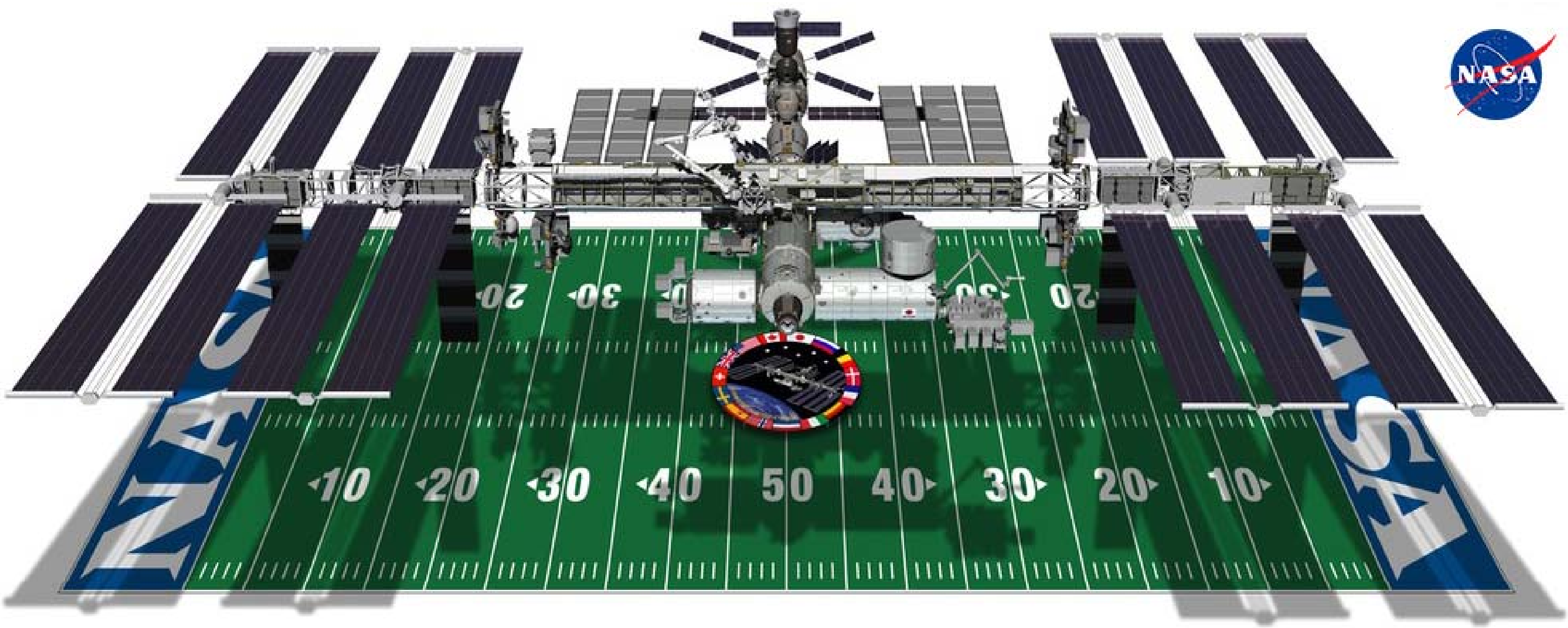
- **Platforms**. Given the short life of the ISS, agencies should leverage it to the extent feasible to test AM and AM parts.

Recommendations (cont.)

- **Cooperation, coordination and collaboration**. Instead of stove-piped parallel development in multiple institutional settings, it is critical that there be cooperation, coordination and collaboration <u>within and across agencies, sectors, and nations</u>. It would be useful to develop working groups, conferences and leverage existing efforts such as the *America Makes*.

- **Education and training**. Agencies need to <u>develop capabilities</u> related to relevant fields such as material science and others that would be important for the development of the field of AM.

MANUFACTURING THE FUTURE IN SPACE



The International Space Station – a five bedroom, two bathrooms, and 1 gymnasium house; Weighs ~ 1 million pounds. It took:

- 89 Russian and 37 Space Shuttle launches
- 168 Spacewalks spanning 1061 hours

COULD THE NEXT SPACE STATION OR DEEP SPACE MISSION BE MANUFACTURED IN SPACE?

QUESTIONS

BACKUP SLIDES

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