National Aeronautics and Space Administration

Engineering Design for Human Exploration

Human Exploration Project I
Energy and Power

A Standards-Based High School Unit Guide

Engineering byDesign™

Advancing Technological Literacy

A Standards-Based Program Series

This unit coordinates with the ITEA EbD™ Course: *Engineering Design.*

HS

International Technology Education Association
Center to Advance the Teaching of Technology and Science

Educational Product	
Educators	Grades 9–12

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Teacher Notes

This unit is intended to serve as part of a high school experience for students who are interested in exploring Technology Education and/or Pre-Engineering. In terms of Science, Technology, Engineering, and Mathematics (STEM) education, this unit primarily focuses upon the "T" and "E" of STEM, with strong linkages to the "S" and "M." The intended audience includes students in Grades 11or 12. While there are no prerequisites, prior experience in technological literacy through Technology Education is helpful.

Preface

Engineering Design for Human Exploration
A Standards-Based High School Unit

Acknowledgments

Many individuals committed to developing high school technological literacy made this publication possible. Their strong commitment to developing standards-based technology resources is reflected in this guide. Special thanks are expressed to the following:

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The ITEA-CATTS Human Exploration Project (HEP)
People, Education, and Technology

In May 2005, ITEA was funded by the National Aeronautics and Space Administration (NASA) to develop curricular units for Grades K–12 on Space Exploration. The units focus on aspects of the themes that NASA Engineers and Scientists—as well as future generations of explorers—must consider, such as Energy and Power, Transportation, and Lunar Plant Growth Chambers (the STS-118 Design Challenges). Moreover, the units are embedded within a larger Model Program for technology education known as Engineering byDesign™.

The Human Exploration Project (HEP) units have several common characteristics. All units:

- Are based upon the Technological Literacy standards (ITEA, 2000/2007).
- Coordinate with Science (AAAS, 1993) and Mathematics standards (NCTM, 2000).
- Utilize a standards-based development approach (ITEA, 2005).
- Stand alone and coordinate with ITEA-CATTS Engineering byDesign™ curricular offerings.
- Reflect a unique partnership between NASA scientists and engineers and education professionals.

These unit guides are designed to be practical and user-friendly. ITEA welcomes feedback from users in the field as we continually refine these curricular products, ensuring that the content remains as dynamic as the technological world in which we live. Please e-mail <ebd@iteaconnect.org> or call 703–860–2100.

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Engineering Design for Human Exploration A Standards-Based High School Unit

Unit Overview

Big Idea

Human exploration of the solar system requires the systematic identification and resolution of a myriad of problems for which there are multiple solutions. Engineering design focuses on designing solutions for problems to which many alternative solutions can be developed. Engineers, as solution designers, must have a systematic process for determining the best solution from among several alternatives.

Teacher's Note: Big ideas should be made explicit to students by writing them on the board and/or reading them aloud.

Purpose of Unit

Through the 5E learning cycle model, correlated with an engineering design process model, students acquire the abilities to apply the engineering design process through the development of solutions to problems associated with traveling to and living on the lunar surface. The unit was designed specifically to assist student understanding of the engineering design process and its applications.

Unit Objectives

Students will learn to:

1. Apply the 12 steps of the engineering design process in the development of a product or system to address NASA lunar exploration surface power generation problems.
2. Communicate information formally, including significant data, using current presentation strategies.
3. Work collaboratively and safely to solve specific engineering design problems.

Engineering Design

Engineering educators, over the years, have developed several models of the engineering design process. Depending on the learning audience, educators can choose simple 4-step models or very detailed 16-step models. Most of these models differ on the level of detail provided in the activities. All of the models include the tasks associated with problem recognition and identification, problem delimitation, searches for alternative solutions, systematic testing of solutions, implementation, and reporting. The engineering design process described in *Standards for Technological Literacy: Content for the Study of Technology* (ITEA, 2000/2002/2007), Standard 9, is a 12-step process that is generic, sufficiently detailed, and a systematic model for analyzing and solving problems related to the creation or improvement of products, processes, and services. By applying this engineering design model to various problems, students learn that engineering design is driven by purpose and requirements; is systematic, iterative, and creative; develops multiple solutions to a problem; and assists in the selection of the best solution from among various alternatives.

The 12 engineering design steps as they are applied in this unit are as follows:

1. Defining a problem
2. Brainstorming
3. Researching and generating ideas
4. Identifying criteria and specifying constraints
5. Exploring possibilities
6. Selecting an approach
7. Developing a design proposal
8. Making a model or prototype
9. Testing and evaluating the design using specifications
10. Refining the design
11. Creating or making the final solution
12. Communicating the processes and results

5E Instructional Model

The "5E Instructional Model" developed through Biological Sciences Curriculum Study (BSCS) was intended to help students construct their understanding of science concepts through a structured sequence of learning experiences. The five "E"s—Engagement, Exploration, Explanation, Extension, and Evaluation—are used as a guide for lesson planning. Instruction first Engages students with the items under study. They are guided through the Exploration of the items through structured activities, during which they build their understanding of the items. In the Explanation phase, concepts are clarified as learners articulate their observations and experiences. Students are then asked to Extend their understanding of the concepts by applying them to new situations. The students and their teachers then Evaluate their understandings of the concepts. Enrichment is a sixth step used by the International Technology Education Association (ITEA) to include activities that may be included if time and resources allow to further enhance student understanding.

Engineering Design Model and 5E Instructional Model Combined

The process of designing products, processes, and services, as a lesson planning model, can be correlated to the 5E Instructional Model used in ITEA's Engineering byDesign™ program (Fig.1). This correlation transforms the engineering design process into a lesson-planning model that is supported by the 5E Instructional Model. The 12 steps of engineering design are used as a lesson-planning model in the two lessons of this unit.

Twelve Steps of Engineering Design	Five "E"s
Defining a problem	Engagement
Brainstorming	
Researching and generating ideas	Exploration
Identifying criteria and specifying constraints	
Exploring possibilities	
Selecting an approach	Explanation
Developing a design proposal	
Making a model or prototype	Extension
Specification-based testing and evaluation	
Refining the design	
Creating or making the final solution	Evaluation
Communicating the processes and results	

Figure 1: Model Correlation

Evidence of Learning

Students demonstrate achievement of the unit goals through the systematic completion of a hypothetical problem focused on human space exploration. Acceptable evidence of these goals includes the following:

- Complete and detailed project portfolios that record the design journey the student took to accomplish the specified problems.
- Prototypes, mockups, or models of proposed solutions.
- Presentations proposing and defending proposed solutions.

The project portfolio prepared by the students must exhibit:

- Completion of the 12-step design model.
- Problem identified and a decision to solve the problem.
- Constraints and requirements defined.
- Identification of criteria and constraints.
- Checking and refining of a design that leads to product improvement.
- Analysis of competing design requirements.
- Construction of a prototype or mockup that leads to refinements and improvements.
- Refined prototype.
- Consideration of a variety of factors in the design (e.g., safety, reliability, economic, quality control, environmental issues, manufacturability maintenance and repair, and ergonomics).
- Design evaluation using conceptual, physical, and mathematical models.
- Systematic evaluation of the product and process.
- Communication of the design process.

Instruction

The teacher is expected to provide instruction on the attributes and applications of design and the 12-step engineering design process, remembering that the solution to the problem/scenario is not the goal of the unit. Students should not be evaluated on the novelty or technical nature of their solutions. Rather, students should be evaluated on their use, understanding, and documentation of the engineering design process. Students must provide evidence of their understanding of the design process. The evaluation of the design, itself, should be limited to the degree to which the design meets the design constraints and requirements.

Support Resources

Instructional support for this unit follows the two components identified in the Problem/Scenario description.

- The creation of habitats appropriate for human well-being and productivity.
- Energy and power requirements for lunar surface living.

Even though the simulation of the space and lunar transportation and living conditions cannot be achieved in the high school classroom, student understanding and capabilities can be developed though a single, multidimensional, class-focused activity. To orient students to the problem, a focal activity is suggested that encourages design activities and creative thinking. Specifically, students are introduced to model rocketry during the first few days of the unit. In addition to building and launching a model rocket, students are required to consider the physical characteristics of the payloads their model rockets can carry. Students construct a mockup of their proposed lunar habitat and then disassemble the habitat and package it for transport in model rockets. The mockup is launched and recovered and then reassembled by the students.

Students need to follow the engineering design process to develop solutions to the problem. The solution, a habitat on the lunar surface, can only be achieved through the resolution of other problems that are also addressed through the engineering design process. The instructor should assist the students in focusing on a few elements for each problem. For example, for the lunar habitat, materials, dimensions, and mass should be considered.

Generic Descriptions of the Engineering Design Process

Engagement

Defining the problem

Given a scenario, students, as a class, attempt to determine what the problems might be and how they can be categorized so that the class can be divided into teams. The instructor should facilitate this process, guiding the students to divide the problem into multiple problems that are more manageable.

Brainstorming

Following standard brainstorming processes, each element of the problem should be explored. The goal of the initial brainstorming session is to develop a better understanding of the problems associated with the mission.

Exploration

Researching and generating ideas

Students should research existing technologies and ongoing research in space exploration that are related to their particular component or problem.

Identifying criteria and specifying constraints

Students should identify the criteria, constraints, or requirements that their solutions must meet.

Exploring possibilities

Students should be involved in the search for alternative ways to solve the problems they are studying.

Explanation

Selecting an approach

Identifying several options for solving the problem, students should select and defend a solution. This requires that they apply the criteria and constraints previously identified to the solutions.

Developing the design proposal

Students should develop a design proposal that seeks to persuade others of the viability of their proposed solution. Before beginning the prototyping phase of the project, students must gain instructor and class approval of the design proposal.

Extension

Making a model or prototype

Students should construct a mockup of the space habitat and spacecraft that will allow them to test the feasibility of their design decisions.

Specification-based testing and evaluation

Students should design experiments to test their design specifications.

Refining the design
Students should refine their designs (clearly document the refinements) and develop a final solution.

Evaluation

Creating or making the final solution
Since students will not be able to implement their final solutions, except as a simulation using model rockets, students should report on the simulation results.

Communicating the processes and results
Students should complete a comprehensive project portfolio (report) that clearly documents their designs, decisions, and activities during each phase of the engineering design process.

Unit Lesson Preparation

Teacher Preparation

The laboratory-classroom should provide a flexible, resource-rich learning environment that includes areas for lectures and demonstrations, small-group meetings, design processes, research activities, production and fabrication, product/prototype testing, and analysis. The teacher adapts the learning environment based on the requirements of the unit or lesson.

Tools/Materials/Equipment

- Computers (a standard for both lessons in this unit)
- Computer projector (a standard for this unit)
- Screen (a standard for this unit)
- Overhead projector (a standard for this unit)
- Paper supplies, scissors, graph paper, chart paper, markers
- Model rockets (See ***Lesson Resource 1.1***)
- Residential/commercial floor plans (Various samples of these can be found on the Internet. The idea is to find out what students understand about electrical infrastructure and components.)

Classroom Safety and Conduct

1. Students should follow prescribed program and school safety rules. It is also assumed that every teacher will establish appropriate rules of conduct and a management system to ensure high-performance behavior and interaction with peers by all students. The instructional suggestion is to establish a NASA-type organization that is used to ensure optimization of all engineering design with respect to the lunar exploration initiative for the twenty-first century.
2. A clear set of consequences and rewards should be defined, reviewed, and maintained throughout the school year. Specific rubrics for independent and group work are modeled in many lessons in this unit.
3. During this unit, lessons may suggest that students assume numerous, diverse, and authentic roles found in NASA research centers, such as Marshall, Glenn, and Johnson. This technique offers students the opportunity to learn about "conduct becoming" a professional in engineering, science, or mathematics. It is highly recommended that each instructor offer as much job-task structure as possible so that students can experience the demanding and highly responsible nature of engineering careers.

4. If possible, students should be allowed to assume a wide variety of management and labor positions throughout the entire unit. Some instructors actually assign salaries reflective of the industry and connect some aspects of assessment to a professional review for salary increases based on job performance. This enables students to better understand the issue of connecting ability, performance, work ethics, and attitude to actual career evaluation standards and processes via classroom activities. The more authentic the environment and class procedures, the more student understanding of how engineers perform their work will be enhanced.
5. The use of actual NASA "personnel" charting or NASA "project-task" charting for all group work as well as other simulations found in the unit offers powerful, authentic experiences helping to prepare students for the rigor and challenge of engineering work.
6. Students use tools and equipment in a safe manner and assume responsibility for their safety, as well as the safety of others.
7. Students demonstrate respect and courtesy for the ideas expressed by others in the class.
8. Students show respect and appreciation for the efforts of others.

Standards and Benchmarks

Technology: Standards for Technological Literacy (STL) *(ITEA, 2000/2002/2007)*

- Students will develop abilities to apply the design process. (ITEA/STL 11)
  - Develop and produce a product or system using a design process. (11Q)
  - Evaluate final solutions and communicate observation, processes, and results of the entire design process, using verbal, graphic, quantitative, virtual, and written means, in addition to three-dimensional models. (11R)

Mathematics: Principles and Standards for School Mathematics *(NCTM, 2000)**

- Formulate questions that can be addressed with data and collect, organize, and display relevant data to answer them. (NCTM, Data Analysis and Probability, Grades 9–12)
  - Understand the differences among various kinds of studies and which types of inferences can legitimately be drawn from each.
  - Know the characteristics of well-designed studies, including the role of randomization in surveys and experiments.

Science: Benchmarks for Science Literacy *(AAAS, 1993)***

- Communication Skills (AAAS, 12D, Grades 9–12)
  - Write clear, step-by-step instructions for conducting investigations, operating something, or following a procedure.
  - Use tables, charts, and graphs in making arguments and claims in oral and written presentations.

Student Assessment Tools and/or Methods

(See assessment instruments at end of each lesson.)

- Selected Response Items
- Brief Constructed Response Items
- Performance Rubric

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Lesson 1: Lunar Habitations

Lesson Snapshot

Overview

Big Idea: Concepts for lunar base structures have been proposed long before the dawn of the space age. From science fiction to data collected from lunar observations and the Apollo missions of the 1960s and 1970s, more significant engineering design concepts are being investigated.

Teacher's Note: Big ideas should be made explicit to students by writing them on the board and/or reading them aloud.

Purpose of Lesson: This lesson enables students to understand NASA solutions for communal habitats that will enable humans to live and work on the lunar surface. These concepts are explored through the application of the engineering design process.

Lesson Duration: Twelve hours.

Activity Highlights

Engagement: Students build and launch a payload-style model rocket that will carry a small structure to build with a number of Lego® bricks that can be reassembled into an original structure after launch.

Exploration:

1. Students identify and describe terrestrial constraints and provide unique design solutions found in nearly every structure on Earth, then transfer them to lunar living.
2. Students begin their investigation on lunar structural design concepts by completing a comprehensive investigation using diverse resources, including NASA materials.

Explanation:

1. Students develop a Technology Readiness Level chart to judge the readiness of various technologies.
2. Students discuss the key elements and prime considerations for lunar habitat design.

Extension: Students design and build a highly detailed, scaled model of their proposed lunar habitat.

Evaluation:

1. Rubrics for Twelve-Step Design Process, Brief Constructed Response (BCR), Graphic Organizer, Class Seminar for All Scheduled Meetings, Prototype, and Multimedia Presentation.
2. Model and presentation (based on design brief). This will be an interim presentation, as the final product will still need a power source to be added in Lesson 2.

Enrichment: The entire class could participate in the creation of a full-size Environmental Control and Life Support System (ECLSS) environment located somewhere in the school where students could enter and actually experience a simulated space lab facility.

Lesson 1: Overview

Lesson Duration

- Twelve hours.

Standards/Benchmarks

Technology: Standards for Technological Literacy (STL) *(ITEA, 2000/2002/2007)*

- Students will develop abilities to apply the design process. (ITEA/STL 11)
  - Develop and produce a product or system using a design process. (11Q)
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  - Understand the differences among various kinds of studies and which types of inferences can legitimately be drawn from each.
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Science: Benchmarks for Science Literacy *(AAAS, 1993)***

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  - Write clear, step-by-step instructions for conducting investigations, operating something, or following a procedure.
  - Use tables, charts, and graphs in making arguments and claims in oral and written presentations.

Learning Objectives

Students will learn to:

1. Apply the 12 steps of the engineering design process in the development of a product or system to address NASA lunar exploration surface power generation problems.
2. Communicate information formally, including significant data, using current presentation strategies.
3. Work collaboratively and safely in the solution of specific engineering design problems.

Student Assessment Tools and/or Methods

1. 12-Step Engineering Design Process Assessment Rubric (***Assessment Resource 1***).
2. Brief Constructed Response (BCR) Assessment Rubric (***Assessment Resource 2***).
3. Graphic Organizer Assessment Rubric (***Assessment Resource 3***).
4. Multimedia Presentation Assessment Rubric (***Assessment Resource 4***).
5. Prototype Assessment Rubric (***Assessment Resource 5***).
6. Class Seminar for All Scheduled Meetings Assessment Rubric (***Assessment Resource 6***).

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Resource Materials

Books, periodicals, pamphlets, and websites may provide teachers and students with background information and extensions. Inclusion of a resource does not constitute an endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Print Materials

Berry, C. A. & Smith, M. (1972). What we've learnt from space exploration. *Nutrition Today*, 9(10), 4-11, 29-32.

Bourland, C. T. (1993). The development of food systems for space. *Trends in Food Science and Technology*. 4, 271-276.

Audiovisual Materials

Spampinato, P. (2008). Expandable habitat structures for long duration lunar missions. Retrieved January 16, 2009, from <http://www.nasa.gov/pdf/214674main_Spampinato.pdf>.

Internet Sites

Bryner, J. (2008). Moon dust could be used to build lunar lodgings. Retrieved November 24, 2008, from <http://www.space.com/scienceastronomy/080604-lunar-concrete.html>.

Kortenkamp, D., Bell, S., & Rodriguez, L. (n.d.). Simulating lunar habitats and activities to derive system requirements. Retrieved November 24, 2008, from <http://www.traclabs.com/~korten/publications/exploration05.pdf>.

NASA. (2007). NASA tests lunar habitat in extreme Antarctic environment. Retrieved November 24, 2008, from <http://www.nasa.gov/home/hqnews/2007/nov/HQ_07251_Inflatable_Lunar_Habitat.html>.

NASA. (2007). Camping on the Moon will be one far out experience. Retrieved November 24, 2008, from <http://www.nasa.gov/directorates/esmd/home/inflatable-lunar-hab.html>.

Than, K. (2008). 'Lunar Concrete' may form buildings on the Moon. Retrieved November 24, 2008, from <http://news.nationalgeographic.com/news/2008/06/080604-lunar-cement.html>.

University of Alabama Press Office (2001). Concrete: A promising space technology. Retrieved November 24, 2008, from <http://www.space.com/businesstechnology/technology/space_concrete_010601.html>.

Wickman, J. (2002). Using lunar soil for propellants & concrete. Retrieved November 24, 2008, from <http://www.wickmanspacecraft.com/moon1.html>.

Required Knowledge and Skills

Students should be able to construct or prepare charts and graphs with a variety of data points and other key information. Students should be able to use software applications (Microsoft® Office Suite) to prepare documents and spreadsheets as well as make highly informative, multimedia presentations. Students must be familiar with the engineering design process. Students must be able to conduct a highly effective, efficient, and ethical Internet search. Students must be able to use tools, materials, and equipment safely after review by instructor. In addition, students should be able to create mechanical drawings using CADD software.

Lesson 1: 5E Lesson Plan

Engagement

1. Divide the class into teams of 2–3 students. Provide each team with a payload-style model rocket to build. (See ***Lesson Resource 1.7***.)
2. Build a small structure from Lego®-type bricks that can be disassembled and placed in the payload sections of the student rockets.
3. Launch the rockets and, upon landing and recovery, reassemble the original structure.
4. Explain to students that any structure that is brought to the Moon will need to be prefabricated, disassembled for transport, and reassembled upon arrival on the Moon.

Exploration

1. Concepts for lunar base structures have been proposed since long before the dawn of the space age. From science fiction to data collected from lunar observations and the Apollo missions of the 1960s and 1970s, more significant engineering design concepts are being investigated.
    a. Have the class generate a list of the kinds of structures and materials they feel might be used to create a lunar habitat. Students could be required to prepare a BCR first, which allows them to capture their personal ideas, and then each can contribute to the larger class discussion and final list.
    b. This discussion will probably lead to a deeper understanding of the environmental conditions or "constraints" found on the Moon. This initial exploration activity is designed to simply see what students already know as well as their sources of such information. All ideas are listed and placed for view by the class. Ideas from science fiction should be welcomed.
2. Ask students to identify and describe terrestrial constraints and then transfer them to lunar living. An interesting way to accomplish this is to have student teams (2–3) develop a simple table as shown below. One example is provided in Figure 2.

Terrestrial Structures	
Structural Types	**Typical Materials**
Frame Buildings	Steel, concrete, glass, wood

Figure 2: Sample Table of Terrestrial Structures/Materials

3. Have students review samples of entire floor plans for typical residential or commercial buildings. The idea is to see what they understand regarding electrical infrastructure and components. By starting with terrestrial structures, students can more easily transfer that understanding to the requirements and constraints for lunar systems.
4. Assign each student a different lunar habitat type to research. After 15 minutes, have the students who researched the same habitat type meet to compare notes. The following are offered as some of the most current ideas being investigated by NASA as well as other nations and private contractors: concrete structures (use of lunar dust) (see ***Lesson Resource 1.2***), pneumatic structures (See ***Lesson Resource 1.3***), lavatubes (below lunar surface) (see ***Lesson Resource 1.4***), Metal Frame (typical and exotic alloys) (See ***Lesson Resource 1.5***), Glass Structures, and Hybrid Structures.

5. Student teams report back to the class about what they collectively found concerning their assigned habitat type. As they report, ask that they make comparisons between our terrestrial environment and that of the Moon. As with any structural engineering design problem, the unique and demanding environmental constraints must be addressed.
    a. Some suggestions for “constraints” to be addressed in a chart similar to the one below should include:
        i) Gravitational pull
        ii) Soil or surface type
        iii) Temperature ranges
        iv) Atmosphere conditions
        v) Radiation
        vi) Microbes
        vii) Meterorite/asteroid bombardment
        viii) Quakes (Earth or lunar based)
        ix) Solar flares
        x) Soil density
        xi) Vacuum of space—Moon

Terrestrial Condition	**Lunar Condition**
ex. 1 G	ex. 1/6 G

Figure 3: Environmental Constraint Comparison (Terrestrial-Lunar)

    b. The Student Resources listed above include images of possible design concepts for lunar structures. These images can also serve to assist students as they conduct their research and prepare design concepts appropriate for living and working on the lunar surface. Comparisons can be made via visual images and supporting information between terrestrial and lunar habitats resulting from the unique environmental conditions/constraints.
    c. Students should create sketches that will later be used to build high-quality, scaled models set in a simulated lunar environment.

Explanation

1. NASA has a management tool they use to assess the readiness level of new and emerging technologies. There are nine steps to NASA’s Technology Readiness Levels (TRLs) that range from basic scientific principles to “flight proven” technologies that have flown on successful missions (***Lesson Resource 1.6***). As a class, students develop a set of TRLs for students to use to assess the readiness of the various habitat types they might choose to propose for the lunar surface. As this concept will be new to most students, the teacher should keep it simple and limit the class to four readiness levels. The class should design a chart to use when assessing the various habitat types. This chart will be used again in Lesson 2, when students must design a power source for their lunar habitat.

2. Explain to the students that the activities already completed follow the engineering design process. They have already defined a problem, brainstormed solutions, researched and generated ideas, identified criteria and constraints, and explored possible solutions. During the remainder of the lesson, they will select an approach, develop a design proposal, make a model, test and evaluate the model, refine the design, create a final design, and communicate the process and results. This process will be repeated in Lesson 2, when students must design a power source for their habitat.
3. The teacher should divide the class into teams and allow the team to select a "structural type" using the class-designed TRL. Explain to each teams that they will design and construct a scaled, detailed model, and they will have to explain the benefits of that design. The teacher explains that whatever structural design is selected, the habitat structure should address the following key elements as defined by NASA for effective conditions to support the lunar crew.
    a. Relationships between severe lunar temperature cycles and structural and material fatigue, a real problem for exposed structures.
    b. Structural sensitivity to temperature differentials between different sections of the same component.
    c. Very low-temperature effects and the possibility of brittle fractures.
    d. Outgassing for exposed steels and other effects of a high vacuum on steel, alloys, and advanced materials.
    e. Factors for safety, originally developed for terrestrial structures, will need adjustments for the lunar environment, either up or down, depending on risk calculations.
    f. Reliability and risk must be major components of lunar structures.
    g. Dead and live loads under lunar gravity (1/6 g).
    h. Buckling, stiffening, and bracing requirements for lunar structures, which will be internally pressurized.
    i. Consideration of new failure modes such as those due to high-velocity micrometeorite impacts.
4. The teacher leads a discussion of the prime considerations for any lunar structure design. Students should refer to their Environmental Constraints Comparison Chart from the Exploratory Activity.
    a. Safety and reliability—redundancy
    b. 1/6 g. gravitational pull
    c. Internal pressurization
    d. Shielding
    e. Vacuum
    f. Dust
    g. Ease of construction
    h. Use of local materials (a must)
    i. Transportation
    j. Comfort and convenience

Extension

1. After the research is completed, student teams are challenged to design and build a scaled, detailed model for demonstration purposes. These models could be on a large scale. It is suggested that each team develop their model in a 3 ft × 3 ft area. The teacher can adjust this size as needed depending on material availability and storage of such models. Remind students to leave space on their models for the power source they will develop in Lesson 2.

2. Student models must begin with schematics drawn using CADD programs. These drawings are used to help explain their models and show how key functions actually are addressed with respect to engineering design solutions.
3. Student models should include significant details including appropriate dioramas of moonscapes to achieve an authentic feel. ***Lesson Resource 1.7*** depicts an artist's rendition of a potential early lunar outpost and could be used as an additional resource for students as they develop their diorama.
4. Considerations for a lunar habitat site should include the following:
   - Good conditions for transport operations.
   - Numerous and diverse natural objects and features for scientific investigation.
   - Natural resources, such as oxygen.
5. Life support systems for communal environments—such as those found on space vehicles and planetary habitats—should be addressed by students as part of the final presentation. Students explain where the Environmental Control and Life Support System (ECLSS) components are located and how they function. The habitat should also have an Exercise Countermeasures Laboratory (ECL). This laboratory provides low-mass systems requiring space for astronauts to exercise and maintain healthy bones, cardiovascular health, muscle mass and overall relaxation derived from regular exercise (see ***Lesson Resource 1.8***).
6. Food and nutrition is another critical requirement for a lunar habitat and will require space for the production and storage of food. Early missions required the food to be compact while meeting nutritional needs as defined at the time. Constraints for lunar food products are being addressed by NASA and other organizations. Currently, these constraints include the following:
   - Weight and volume
   - Food acceptability (preferences by crew)
   - Food preparation time
   - Food safety
   - Psychological and nutritional requirements
7. Students should investigate the most contemporary solutions being proposed by NASA and other research institutions for food and nutrition. One example of research has shown the following crops to be the most worthy candidates as ingredients for food products as part of a lunar colony:
   - Wheat
   - White potato
   - Soybean
   - Quinoa
   - Sweet potato
   - Peanut
   - Rice
   - Tomato
   - Mixed greens (lettuce, spinach, chard, etc.)
8. Student research should be applied as part of the habitat extension activity in a proposal for food products with the most nutritious ingredients based on recent research by NASA. Student research should include all key data tables and nutritional values, as well as food product concepts for appealing meals.

Evaluation

Student knowledge, skills, and attitudes are assessed using brief constructed response items and rubrics for the activities. The rubrics should be presented in advance of the activities to familiarize students with the expectations and performance criteria. They should also be reviewed during the activities to guide students in the completion of assignments. The teacher may wish to develop a collection of annotated exemplars of student work based on the rubrics. The exemplars will serve as benchmarks for future assessments and may be used to familiarize students with the criteria for assessment.

Enrichment

1. The entire class participates in the creation of a full-size ECLSS environment located somewhere in the school where students could enter and actually experience a simulated space lab facility. This environment would have replicas of key systems designed using actual NASA specifications. Students could be allowed to offer their own designs for improvements, but would be required to justify such changes with clear explanations of why, based on applied science and mathematics.
2. Smaller student teams could be assigned to address each of the many subsystems that are part of such an environment. It is essential that all subsystems be coordinated by a Project Manager that would ensure smooth and complete integration of all subsystems to create an authentic full-size environmental model, with some functional systems if feasible.
3. The starting point for such an endeavor is to challenge students to revisit their research on the many life support system initiatives sponsored by NASA. The primary focus should be on the ECLSS.
4. As part of the ECLSS, there needs to be an ECL. One of the most challenging design requirements for engineers is to create low-mass systems requiring a space for astronauts to exercise and maintain healthy bones, cardiovascular health, muscle mass, and overall relaxation derived from regular exercise. Long periods in space will require regular and highly structured exercise routines. With this as background, selected student teams should be challenged to apply NASA data on this subject and design a system that will meet strict NASA guidelines for such equipment. Some examples can be found in ***Lesson Resource 1.8***. These visuals are part of a larger presentation and additional resources are available from the NASA Glenn Research Center.
5. As students develop their models, it is suggested that each design team create appropriate schematics and drawings that clearly show how the particular structure appears, with clear explanations for erecting or construction of such structures.

Lesson 2:
Energy and Power for Lunar Habitations

Lesson Snapshot

Overview

Big Idea: In order to live and work on Earth, our homes and places of work have an infrastructure that allows us to be comfortable, safe, healthy, and entertained.

Teacher's Note: Big ideas should be made explicit to students by writing them on the board and/or reading them aloud.

Purpose of Lesson: This lesson enables students to understand NASA solutions for surface power generation systems that will enable humans to live and work on the lunar surface.

Lesson Duration: Five hours.

Activity Highlights

Engagement: One of the key systems for living and working on the Moon is the production of electrical power for many purposes. The following activity will encourage students to think of the different ways humans generate electricity. The teacher presents students with the laboratory setup for an experiment that will demonstrate that we can create an electric current using nothing more than our own bodies.

Exploration: Students meet in their teams from Lesson 1 to brainstorm all the power needs they designed into their habitats. Students then compile a list of human functions away from their habitats that will require power on the lunar surface.

Explanation:

1. Students identify, discuss, explain, and clarify how terrestrial human functions requiring power will be the same on the lunar surface or different.
2. Students complete a K-W-L chart to check prior knowledge regarding NASA surface power generation projects.
3. Students, as part of the project development team, present a multimedia presentation with a model on one of the four types of NASA-sponsored surface power generation systems.

Extension: As part of a project development team, students use the information gained from their research to design an appropriately scaled model that is as detailed as possible. Every effort should be made to produce a high-quality, authentic model with moving parts, if applicable. If appropriate and approved by the instructional team, students should be encouraged to design and build a functional model.

Evaluation:

1. Rubrics for: 12-Step Design Process, Brief Constructed Response (BCR), Graphic Organizer, Class Seminar for All Scheduled Meetings, Prototype, Multimedia Presentation, and Extended Constructed Response.
2. Model and presentation (based on design brief). This product will include the habitat and power source.

Enrichment:

1. Students can be challenged to investigate a cutting-edge technology for surface power generation.
2. Students can be challenged to locate recent announcements by NASA that offer funding for further development of surface power generation systems that have been presented in this lesson or represent cutting-edge or emerging technologies.
3. The Rochester Institute of Technology has a Nanopower Research Laboratory in the College of Science that conducts research on the generation and storage or energy using nanostructured materials, especially photovoltaic, waste heat recovery, battery and fuel cell technology. Students should be challenged to investigate the work being done at this school, as well as other institutions or engineering organizations.

Lesson 2: Overview

Lesson Duration

- Five hours.

Standards/Benchmarks

Technology: Standards for Technological Literacy (STL) *(ITEA, 2000/2002/2007)*

- Students will develop abilities to apply the design process. (ITEA/STL 11)
  - Develop and produce a product or system using a design process. (11Q)
  - Evaluate final solutions and communicate observation, processes, and results of the entire design process, using verbal, graphic, quantitative, virtual, and written means, in addition to three-dimensional models. (11R)

Mathematics: Principles and Standards for School Mathematics *(NCTM, 2000)**

- Formulate questions that can be addressed with data and collect, organize, and display relevant data to answer them. (NCTM, Data Analysis and Probability, Grades 9–12)
  - Understand the differences among various kinds of studies and which types of inferences can legitimately be drawn from each.
  - Know the characteristics of well-designed studies, including the role of randomization in surveys and experiments.

Science: Benchmarks for Science Literacy *(AAAS, 1993)***

- Communication Skills (AAAS, 12D, Grades 9–12)
  - Write clear, step-by-step instructions for conducting investigations, operating something, or following a procedure.
  - Use tables, charts, and graphs in making arguments and claims in oral and written presentations.

Learning Objectives

Students will learn to:

1. Apply the 12 steps of the engineering design process in the development of a product or system to address NASA lunar exploration surface power generation problems.
2. Communicate information formally, including significant data, using current presentation strategies.
3. Work collaboratively and safely in the solution of specific engineering design problems.

** Standards are listed with the permission of the National Council of Teachers of Mathematics (NCTM). NCTM does not endorse the content or validity of these alignments.*

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Student Assessment Tools and/or Methods

1. 12-Step Engineering Design Process Assessment Rubric (***Assessment Resource 1***).
2. Brief Constructed Response (BCR) Assessment Rubric (***Assessment Resource 2***).
3. Graphic Organizer Assessment Rubric (***Assessment Resource 3***).
4. Multimedia Presentation Assessment Rubric (***Assessment Resource 4***).
5. Prototype Assessment Rubric (***Assessment Resource 5***).
6. Class Seminar for All Scheduled Meetings Assessment Rubric (***Assessment Resource 6***).
7. Extended Constructed Response Assessment Rubric (***Assessment Resource 7***).

Resource Materials

Books, periodicals, pamphlets, and websites may provide teachers and students with background information and extensions. Inclusion of a resource does not constitute an endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Print Materials

Mayer, A. (1992). Power sources for lunar bases. In Russell J. Miller (Ed.), Engineering, construction, and operations in space III. American Society of Civil Engineers.

Audiovisual Materials

Naininger, J. J. (2007). Energy storage & power systems: Technology needs & gaps. Retrieved January 16, 2009, from <http://www.nasa.gov/pdf/203076main_TEC%20Power%20Pitch.pdf>.

Internet Sites

Fuelcells.org. (n.d.). Retrieved November 24, 2008, from <http://www.fuelcells.org/?gclid=COjThff6jpcCFRxNagodyUoK_g>.

Kazan, C. (2008). Solar power from the Moon's peaks of eternal light. The Daily Galaxy. Retrieved November 24, 2008, from <http://www.dailygalaxy.com/my_weblog/2008/03/solar-power-fro.html>.

Lockheed Martin. (2002). Astronauts train with space station solar arrays. Retrieved November 24, 2008, from <http://spaceflightnow.com/news/n0203/30arrays/>.

National Renewable Energy Laboratory. (2008). Hydrogen & fuel cells research. Retrieved November 24, 2008, from <http://www.nrel.gov/hydrogen/>.

National Space Society. (n.d.). Space solar power. Retrieved November 24, 2008, from http://www.nss.org/settlement/ssp/.

Potter, S.D., Willenberg, H. J., Henley, M.W., & Kent, S. R. (n.d.). Architecture options for space solar power. Retrieved November 24, 2008, from <http://www.ssi.org/Potter_SSP_99_SSI.pdf>.

Science Daily. (2007). Nano flakes may revolutionize solar cells. Retrieved November 24, 2008, from <http://www.sciencedaily.com/releases/2007/12/071218105420.htm>.

Science Daily. (2008). Toward the next generation of high-efficiency plastic solar cells. Retrieved November 24, 2008, from <http://www.sciencedaily.com/releases/2008/03/080317114050.htm>.

U.S. Department of Energy. (n.d.). RTG–history and new horizons. Retrieved November 24, 2008, from <http://www.osti.gov/accomplishments/rtg.html>.

Required Knowledge and Skills

Students should be able to construct or prepare charts and graphs with a variety of data points and other key information. Students should be able to use software applications (Microsoft® Office Suite) to prepare documents and spreadsheets as well as make highly informative, multimedia presentations. Students must be familiar with the engineering design process. Students must be able to conduct a highly effective, efficient, and ethical Internet search. Students must be able to use tools, materials, and equipment safely after review by instructor. In addition, students should be able to create mechanical drawings using CADD software.

Lesson 2: 5E Lesson Plan

Engagement

1. One of the key systems to living and working on the Moon is the production of electrical power for many purposes. The following activity will encourage students to think of the different ways humans generate electricity.
2. The teacher presents students with the laboratory setup for an experiment that will demonstrate that we can create an electric current using nothing more than our own bodies.

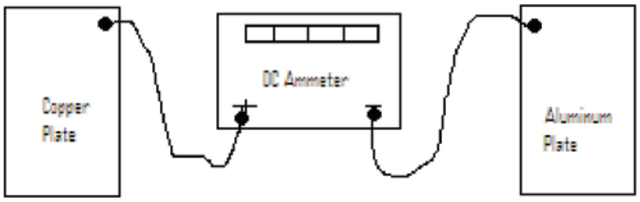


Figure 4: Laboratory Setup for Human Battery Demonstration

3. Working in pairs, students record their predictions of what will happen when they place their hands on the metal plates. Then, students:
    a. Place one hand on each metal plate. (Note: They should see an electric current generated on the meter. If they do not see a reading, then simply reverse the connections. If they still do not see a reading, then they may need to clean the metal plates.)
    b. Record the meter readings.
    c. Wet hands and place one hand on each plate.
    d. Record the meter readings.
    e. Write a brief statement explaining what has occurred.
    f. List other ways they might know of to generate an electric current.
4. Students meet in their teams from Lesson 1 to brainstorm all the power needs they designed into their habitats.
    a. Diagrams and schematics of residential electrical systems here on Earth can be created by students and then the same type of drawings would be created for proposed lunar environments where people would live and work.
    b. Challenge students to select one electrical device that they use frequently and value, and have them prepare a detailed description backwards, showing how the electrical power used to operate the device results from many stages or levels of infrastructure. For example, one student might select their Apple® iPod, while another might select their personal computer, and another might select a microwave oven. Each prepares a very detailed analysis (Extended Constructed Response [ECR]) of all the components and systems that provide power to run the product. The primary purpose for this exploratory activity is to see if students can understand and explain how power generation is achieved here on Earth and how that need for power is essential for so many human functions.
    c. An interesting measurement for Earth-based electrical power systems is to determine the mass-to-unit power ratio of these systems. Since our terrestrial systems can be built here and do not have to be hauled into outer space and then landed safely on another planet, it is less challenging to design and build effective power systems for our habitats. However, the enormous challenge of living and working on the surface of the Moon, and eventually Mars and other planets, is staggering. Students should

be challenged to determine the mass-to-unit power ratio for a few common, everyday electrical devices or systems. A few are suggested below:

- Standard automobile battery
- Residential heat pump
- Gasoline generator
- Computer battery
- Watch battery
- Electrical requirements for a typical home (2,000 square feet)

d. NASA and other organizations that may be involved with the design and development of surface power systems for lunar environments must address numerous and diverse constraints. The critical issue for optimized development of surface power systems is the mass-per-unit power ratio, depending on the specific electrical demands of the required system. This is the key factor that NASA must address in all systems that require electrical power—and nearly all do. Students working in small teams (2–3) complete a table similar to the example below (see Fig. 5).

Device or System	**Power Output or Need**	**Mass/Weight**	**Mass to Unit Power Ratio**
Automobile Battery	14 amps	22 lb	

Figure 5. Sample of Table Describing the Power Output or Need, Mass/Weight, and Mass-to-Unit Power Ratio of a Device or System

e. Once this is established, it is time for students to transition to how power generation might be achieved for living and working on the lunar surface.

5. Students should take the many human functions that require electrical power here on Earth and discuss which of these functions must also require electrical power on the Moon. Students should be engaged in a discussion led by the teacher, to generate a list of human functions that must also be supported while living and working on the lunar surface. In some cases, it may be evident that electrical power is not needed for some key functions. Some critical systems should be presented to students for consideration. Power needs of some systems are listed in Lesson Resource 2.1. These might include, but are not limited to the following:
   a. Heating and cooling structures
   b. Refrigeration
   c. Food storage
   d. Tool and machine use
   e. Waste management
   f. Communication
   g. Entertainment
   h. Physical conditioning/health monitoring

Explanation

1. Working in their teams from Lesson 1, students will need to determine how they will generate the power needed for the human activities identified in the Exploration section.
   a. The teacher leads a discussion of the electrical generating methods used on Earth that could be used on the lunar surface. These include the following:
      - Nuclear fission
      - Fuel cells
      - Solar thermal collectors
      - Solar photovoltaic
   b. Other technologies being studied for space applications include the following:
      - Nuclear fusion
      - Nuclear decay
   c. This discussion may lead to power storage methods, which include the following:
      - Chemical
      - Mechanical
      - Thermal
      - Electrical
2. Assign each student a different type of electrical power generation system to research and have them complete a K-W-L (what they Know, what they Want to know, and what they Learned) chart on their assigned system. After 15 minutes, students who researched the same power generation system type meet to compare notes. Each group reports the results of their research. Students return to their teams and, using the TRL they developed in Lesson 1, select a method to generate the power needed for their habitat. Information can be found in ***Lesson Resource 2.2***, ***Lesson Resource 2.3***, ***Lesson Resource 2.4***, and ***Lesson Resource 2.5***.

Extension

1. Student teams use the information gained from their research and activities to design an appropriately scaled model that is as detailed as possible to power the habitats they designed in Lesson 1. Every effort should be made to produce a high-quality, authentic model, with moving parts if applicable. If appropriate and approved by the teacher, students can design and build a functional model.
2. Each student team presents a multimedia presentation with a model of their planned habitat and NASA-sponsored surface power generation systems. Students should do the following:
   a. Display and describe their team models, with appropriate labeling, to a variety of audiences to inform them of how this power system functions at a very high level of detail and accuracy.
   b. Discuss, explain, and clarify a table showing the mass-to-unit power ratio for Earth-based systems compared to lunar-based systems.
   c. Identify, discuss, explain, and clarify which terrestrial human functions requiring power will be the same and which will be different.

Evaluation

Student knowledge, skills, and attitudes are assessed using brief, constructed response items, extended constructed response items, and rubrics for the activities. The rubrics should be presented in advance of the activities to familiarize students with the expectations and performance criteria. They should also be reviewed during the activities to guide students in the completion of assignments. The teacher may wish to develop a collection of annotated exemplars of student work based on the rubrics. The exemplars will serve as benchmarks for future assessments and may be used to familiarize students with the criteria for assessment.

Enrichment

See ***Lesson Resource 2.6***.

References

Books, periodicals, pamphlets, and websites may provide teachers and students with background information and extensions. Inclusion of a resource does not constitute an endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

American Association for the Advancement of Science (AAAS). (1993). *Benchmarks for science literacy*. New York: Oxford University Press: Author.

Apogee. (n.d.). Dynamo. Retrieved January 16, 2009, from <http://www.apogeerockets.com/dynamo.asp>.

Berry, C. A. & Smith, M. (1972). What we've learnt from space exploration. *Nutrition Today*, 9(10), 4–11, 29–32.

Bourland, C. T. (1993). The development of food systems for space. *Trends in Food Science and Technology*. 4, 271–276.

Bryner, J. (2008). *Moon dust could be used to build lunar lodgings*. Retrieved November 24, 2008, from <http://www.space.com/scienceastronomy/080604-lunar-concrete.html>.

Cataldo, R. (2006). *Overview of planetary power system options for education* (Presentation to ITEA Human Exploration Project Authors November 2006 at Glenn Research Center). Brooke Park, OH.

Estes. (n.d.). Rockets. Retrieved January 16, 2009, from <http://www.estesrockets.com/index.php#>.

Fuelcells.org. (n.d.). Retrieved November 24, 2008, from <http://www.fuelcells.org/?gclid=COjThff6jpcCFRxNagodyUoK_g>.

Gruener, J. E. (2006). *Lunar exporation* (Presentation to ITEA Human Exploration Project Authors November 2006 at Johnson Space Center). Houston, TX.

International Technology Education Association (ITEA). (2000/2002/2007). *Standards for technological literacy: Content for the study of technology*. Reston, VA: Author

Jernigan, M. (2006). *Challenges for humans living off Earth* (Presentation to ITEA Human Exploration Project Authors November 2007 at Johnson Space Center). Houston, TX.

Kazan, C. (2008). Solar power from the Moon's peaks of eternal light. *The Daily Galaxy*. Retrieved November 24, 2008, from <http://www.dailygalaxy.com/my_weblog/2008/03/solar-power-fro.html>.

Kortenkamp, D., Bell, S., & Rodriguez, L. (n.d.). *Simulating lunar habitats and activities to derive system requirements*. Retrieved November 24, 2008, from <http://www.traclabs.com/~korten/publications/exploration05.pdf>.

Lockheed Martin. (2002). *Astronauts train with space station solar arrays.* Retrieved November 24, 2008, from <http://spaceflightnow.com/news/n0203/30arrays/>.

Mayer, A. (1992). Power sources for lunar bases. In Russell J. Miller (Ed.), *Engineering, construction, and operations in space III*. American Society of Civil Engineers.

Naininger, J. J. (2007). Energy storage & power systems: Technology needs and gaps. Retrieved January 16, 2009, from <http://www.nasa.gov/pdf/203076main_TEC%20Power%20Pitch.pdf>.

NASA. (2008). NASA developing fission surface power technology. Retrieved January 16, 2009, from <http://www.nasa.gov/home/hqnews/2008/sep/HQ_08-227_Moon_Power.html>.

NASA. (2007). Lighting up the lunar night with fuel cells. Retrieved January 16, 2009, from <http://www.nasa.gov/exploration/home/lunar_fuel_cell.html>.

NASA. (2007). *NASA tests lunar habitat in extreme Antarctic environment*. Retrieved November 24, 2008, from <http://www.nasa.gov/home/hqnews/2007/nov/HQ_07251_Inflatable_Lunar_Habitat.html>.

NASA. (2007). *Camping on the Moon will be one far out experience.* Retrieved November 24, 2008, from <http://www.nasa.gov/directorates/esmd/home/inflatable-lunar-hab.html>.

NASA. (2006). *ECL quad chart and general information* (Presentation to ITEA Human Exploration Project Authors November 2006 at Glenn Research Center). Brooke Park, OH.

NASA. (2003). *Introduction to planetary science: Lava tube*. Retrieved January 16, 2009, from <http://nai.arc.nasa.gov/insight/insight_albums/5/>.

NASA. (2003). *TransHab concept*. Retrieved January 16, 2009, from <http://spaceflight.nasa.gov/history/station/transhab/>.

National Council of Teachers of Mathematics (NCTM). (2000). *Principles and standards for school mathematics*. Reston, VA: Author.

National Renewable Energy Laboratory. (2008). *Hydrogen & fuel cells research*. Retrieved November 24, 2008, from <http://www.nrel.gov/hydrogen/>.

National Space Society. (n.d.). *Space solar power*. Retrieved November 24, 2008, from <http://www.nss.org/settlement/ssp/>.

Potter, S. D., Willenberg, H.J., Henley, M.W., & Kent, S.R. (n.d.). *Architecture options for space solar power*. Retrieved November 24, 2008, from <http://www.ssi.org/Potter_SSP_99_SSI.pdf>.

Quest. (n.d.) The outfitter for aerospace education. Retrieved January 16, 2009, from <http://www.questaerospace.com/>.

Science Daily. (2007). *Nano flakes may revolutionize solar cells*. Retrieved November 24, 2008, from <http://www.sciencedaily.com/releases/2007/12/071218105420.htm>.

Science Daily. (2008). *Toward the next generation of high-efficiency plastic solar cells*. Retrieved November 24, 2008, from <http://www.sciencedaily.com/releases/2008/03/080317114050.htm>.

Spampinato, P. (2008). *Expandable habitat structures for long duration lunar missions*. Retrieved January 16, 2009, from <http://www.nasa.gov/pdf/214674main_Spampinato.pdf>.

Than, K. (2008). *'Lunar Concrete' may form buildings on the Moon*. Retrieved November 24, 2008, from <http://news.nationalgeographic.com/news/2008/06/080604-lunar-cement.html>.

University of Alabama Press Office (2001). *Concrete: A promising space technology.* Retrieved November 24, 2008, from <http://www.space.com/businesstechnology/technology/space_concrete_010601.html>.

U.S. Department of Energy. (n.d.). RTG–*history and new horizons*. Retrieved November 24, 2008, from <http://www.osti.gov/accomplishments/rtg.html>.

Wickman, J. (2002). *Using lunar soil for propellants & concrete*. Retrieved November 24, 2008, from <http://www.wickmanspacecraft.com/moon1.html>.

Appendices
Resource Documents

12-Step Engineering Design Process Assessment Rubric

Category	Below Target	At Target	Above Target
Defining the Problem	Rephrases the problem with limited clarity.	Rephrases the problem clearly.	Rephrases the problem clearly and precisely.
Brainstorming	Contributes few or implausible ideas.	Contributes a plausible idea.	Contributes multiple plausible ideas.
Researching and Generating Ideas	Contributes ideas but without documented research. Produces incomplete sketches. Does not present a concept.	Contributes one plausible idea based on documented research. Produces marginally accurate pictorial and orthographic sketches of design concepts.	Contributes multiple plausible ideas based on documented research. Produces accurate pictorial and orthographic sketches of design concepts.
Identifying Criteria and Specifying Constraints	Does not restate the criteria clearly and fails to identify constraints.	Restates the criteria clearly and identifies several constraints.	Restates the criteria clearly and precisely and identifies many constraints.
Exploring Possibilities	Inadequately analyzes the pluses and minuses of a variety of possible solutions.	Satisfactorily analyzes the pluses and minuses of a variety of possible solutions.	Thoroughly analyzes the pluses and minuses of a variety of possible solutions.
Selecting an Approach	Selection of solution is not based on consideration of criteria and constraints.	Selects a promising solution based on criteria and constraints.	Selects a promising solution based on a thorough analysis criteria and constraints with high quality.
Developing a Design Proposal	Design proposal is inadequate, lacking pertinent information.	Design proposal is adequate, containing all pertinent elements.	Design proposal is accurate and comprehensive.
Making a Model or Prototype	Prototype meets the task criteria to a limited extent.	Prototype meets the task criteria.	Prototype meets the task criteria in insightful ways.
Testing and Evaluating the Design Using Specifications	Testing and evaluation processes are inadequate.	Testing and evaluation processes are adequate for refining the problem solution.	Testing processes are innovative.
Refining the Design	Refinement based on testing and evaluation is not evident.	Refinements made based on testing and evaluation results.	Significant improvement in the design is made based on prototype testing and evaluation.
Creating or Making It	Finished solution (product) fails to meet specifications.	Finished solution (product) meets specifications.	Finished solution (product) exceeds specifications.
Communicating Processes and Results	Solution presented with limited accuracy. Limited supporting evidence on how the solution meets the task criteria.	Solution presented accurately. Some supporting evidence on how the solution meets the task criteria.	Solution presented concisely with clarity and accuracy. Extensive supporting evidence on how the solution meets the task criteria.
Comment	Comment	Comment	Comment

Brief Constructed Response (BCR) Assessment Rubric

Lesson 1: Make a list of structural types and materials that might be used in a lunar habitat (to assess prior knowledge).

Lesson 2: Write a statement about typical electrical control devices found in Earth-based habitats.

Category	Below Target	At Target	Above Target
Understanding	Response demonstrates an implied, partial, or superficial understanding of the text and/or the question.	Response demonstrates an understanding of the text.	Response demonstrates an understanding of the complexities of the text.
Focus	Lacks transitional information to show the relationship of the support to the question.	Addresses the demands of the question.	Exceeds the demands of the question.
Use of Related Information	Uses minimal information from the text to clarify or extend meaning.	Uses some expressed or implied information from the text to clarify or extend meaning.	Effectively uses expressed or implied information from the text to clarify or extend meaning.
Comments	Comments	Comments	Comments

Graphic Organizer Assessment Rubric

Category	Below Target	At Target	Above Target
Arrangement of Concepts	Main concept not clearly identified; subconcepts don't consistently branch from main idea.	Main concept easily identified; most subconcepts branch from main idea.	Main concept easily identified; subconcepts branch appropriately from main idea.
Links and Linking Lines	Linking lines not always pointing in correct direction; linking words don't clarify relationships between concepts; hyperlinks don't function or fail to enhance the topic.	Most linking lines connect properly; most linking words accurately describe the relationship between concepts; most hyperlinks effectively used.	Linking lines connect related terms/point in correct direction; linking words accurately describe relationship between concepts; hyperlinks effectively used.
Graphics	Graphics used inappropriately and excessively; graphics poorly selected and don't enhance the topic; some graphics are blurry and ill-placed.	Graphics used appropriately most of the time; most graphics selected enhance the topic, are of good quality, and are situated in logical places on the page.	Graphics used appropriately; greatly enhance the topic and aid in comprehension; are clear, crisp, and well situated on the page.
Content	Contains extraneous information; is not logically arranged; contains numerous spelling and grammatical errors.	Reflects most of the essential information; is generally logically arranged; concepts presented without too many excess words; fewer than three misspellings or grammatical errors.	Reflects essential information; is logically arranged; concepts succinctly presented; no misspellings or grammatical errors.
Text	Font too small to read easily; more than four different fonts used; text amount is excessive for intended audience.	Most text is easy to read; uses no more than four different fonts; amount of text generally fits intended audience.	Easy to read/appropriately sized; no more than three different fonts; amount of text is appropriate for intended audience; boldface used for emphasis.
Design	Cluttered design; low in visual appeal; requires a lot of scrolling to view entire diagram; choice of colors lacks visual appeal and impedes comprehension.	Design is fairly clean, with a few exceptions; diagram has visual appeal; four or fewer symbol shapes; fits page well; uses color effectively most of time.	Clean design; high visual appeal; four or fewer symbol shapes; fits page without a lot of scrolling; color used effectively for emphasis.
Knowledge Gained	Student demonstrates a lack of knowledge about the content and the processes used to create the poster.	Student can accurately answer most questions related to content and the processes used to create the poster.	Student can accurately answer all questions related to content and the processes used to create the poster.
Comments	Comments	Comments	Comments

Multimedia Presentation Assessment Rubric

Category	Below Target	At Target	Above Target
Content/Accuracy	Content confusing or contains more than one factual error.	Most content accurate, but there is one piece of information that seems inaccurate.	All content throughout the presentation accurate. No factual errors.
Sequencing of Information	No clear plan for the organization of information.	Most information is organized in a clear, logical way. One slide or piece of information out of place.	Information organized in a clear, logical way. Easy to anticipate the next element.
Effectiveness	Lacking several key elements and has inaccuracies. Completely inconsistent with driving question.	Lacking a key element. Consistent with driving question.	Includes all material needed to give a good understanding of the topic.
Use of Graphics	Graphics unattractive and detract from the content of the presentation.	A few graphics unattractive, but all support the topic of the presentation.	All graphics attractive (size and colors) and support the topic of the presentation.
Text/Font Choice and Formatting	Difficult to read the text material.	Format carefully planned to enhance readability.	Formats (color, bold, italic) carefully planned to enhance readability and content.
Spelling and Grammar	More than two grammatical and/or spelling errors.	One or two misspellings but no grammatical errors.	No misspellings or grammatical errors.
Delivery	Spoke a little faster or slower than necessary, or too quietly or loudly. Used unacceptable grammar. Failed to maintain eye contact. Relied too much on their notes.	Spoke at a good rate. Volume appropriate. Good grammar. Maintained some eye contact with audience.	Spoke at a good rate. Volume excellent for setting. Good grammar. Maintained eye contact with audience.
Comments	Comments	Comments	Comments

Prototype Assessment Rubric

Category	Below Target	At Target	Above Target
Prototype Concept	Loosely based on group's research. Major specification errors present but few in number. Little consideration given to facilitate construction, operation, or maintenance.	Clearly based upon group's research. Minor specification errors or omissions present. Evidence of consideration given to construction, maintenance, and operation.	Clearly based upon group's research. Plans are complete and technically specific. Ease of construction, operation, and maintenance are incorporated in plans. Plans well documented as technical drawings with dimensions and tolerances.
Prototype Construction	Constructed to be functional, but not well executed. Numerous workmanship defects present.	Adequately constructed, but with some obvious defects. Strict adherence to design notes/plans not observed.	Constructed in a highly professional manner, free of workmanship defects. No temporary 'jury rigs" present. Constructed in accordance of dimensions and tolerances specified by design notes.
Aesthetics	No attempt was made to address the appearance of the prototype.	Prototype is neat, clean, and uncluttered.	Prototype appears to be professionally constructed. It includes colors, logos, or other visual additions that give additional professional appearance.
Prototype Test Planning	Rudimentary tests planned, procedures incomplete, or test sequence illogical or impossible.	Not all functions are to be tested. Test procedures completed. Superfluous tests performed. Test plan reveals full review of prototype integrated with prototype construction.	All functions of the prototype have test procedures written. Test procedures include the details mentioned in the Background Narrative. Sequencing of tests on prototype subsystems is logical and does not interfere with construction progress of prototype.
Testing the Prototype	Minor deviations occur regarding procedures. Data is missed or testers unfamiliar with what they are doing and/or why.	Test procedures are followed. Correct data is collected. Tests stopped if unsafe conditions occur.	Tests procedures are followed. Correct data is collected. Tests occur at the appropriate times during prototype construction. Persons conducting the tests are knowledgeable regarding the reason for the test, the reason for each step in the procedure, and the significance of data collected.
Evaluating the Tests	Minimal conclusions drawn from test results. Data collected but not evaluated.	Test results are analyzed, some oversights evident. Reason for failure identified but not investigated to high level.	Test results are compared with acceptable (expected) results. Success or failure determined. Reasons for failure, if applicable, are identified and investigated to deep level.
Prototype Improvement	Test evaluation results in no suggestions for improvement and/or no research done along lines of possible improvement.	Test evaluation results in suggestions for improvement, but no research conducted. Little additional documentation.	Test evaluation results in research, which results in ideas for improvement. Improvement(s) made as resources permit. Improvements documented as revisions to drawings/plans.
Comments	Comments	Comments	Comments

Class Seminar for All Scheduled Meetings Assessment Rubric

Category	Below Target	At Target	Above Target
Participation	Unacceptable interaction and participation with numerous interruptions or off-topic discussions.	Adequate participation offering valuable comments at times, with only occasional interruption of others.	Active level of participation, offering solid comments and ideas but not overbearing, allowing others to engage in discussion.
Contribution	Rarely offers appropriate comments and seeks to disrupt the meeting.	Comments are appropriate and on topic, with some ideas of high value, enabling good discussion of seminar topic.	Comments and ideas are of high value and enable more intense discussion of seminar topic.
Cooperation	Exhibited little courtesy toward others through inappropriate comments and behavior during meeting.	Appropriate level of courtesy toward others enabling good discussion on seminar topic and little disruption observed.	High level of courtesy toward others facilitating engaging and topical discussion on selected topics.
Topic Focus	Not focused on topic and seeks to disrupt with inappropriate questions and comments throughout the meeting.	Comments usually on target and appropriate, including questions and topical discourse during entire meeting.	Comments are always focused on seminar topic, including questions and discourse with others during entire meeting.
Comments	Comments	Comments	Comments

Extended Constructed Response (ECR) Assessment Rubric

Identify and explain the typical systems found in Earth-based habitats needing electrical power linked to human functions or needs.

Category	Below Target	At Target	Above Target
Context and Argument	Context inappropriate. Argument unsatisfactory.	Context appropriate. Argument satisfactory.	Context appropriate. Argument satisfactory. Clearly stated thesis included.
Evidence	Evidence is largely missing or generalized.	Ample and appropriate evidence provided.	Abundant, relevant specifics (names, events, legislation, court decisions, etc.) provided. Includes obscure, but important evidence. Thorough chronology.
Analysis	Minimal analysis or fallacious reasoning.	Organizes argument and uses data to support conclusions. Recognizes causation, change, and continuity.	Well-reasoned cause-and-effect arguments. Fully explained conclusions. Refers to views of others.
Historical Accuracy	Many errors.	May have a few errors. Mistakes may slightly hinder argument, but do not detract from the overall accuracy.	Virtually error-free; minor mistakes do not compromise argument.
Thoroughness	Covers question superficially. May not complete all tasks.	Covers entire question, but may be slightly imbalanced.	Covers all areas of question in approximate proportions to their importance.
Presentation	Inconsistent organization. Grammatical errors cloud argument to a major degree.	Uses clear language. Well organized. Contains few grammatical errors.	Uses clear, appropriate, and precise language. Cohesive organization. Very few grammatical errors.
Comment	Comment	Comment	Comment

Payload-Style Model Rockets

Books, periodicals, pamphlets, and websites may provide teachers and students with background information and extensions. Inclusion of a resource does not constitute an endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

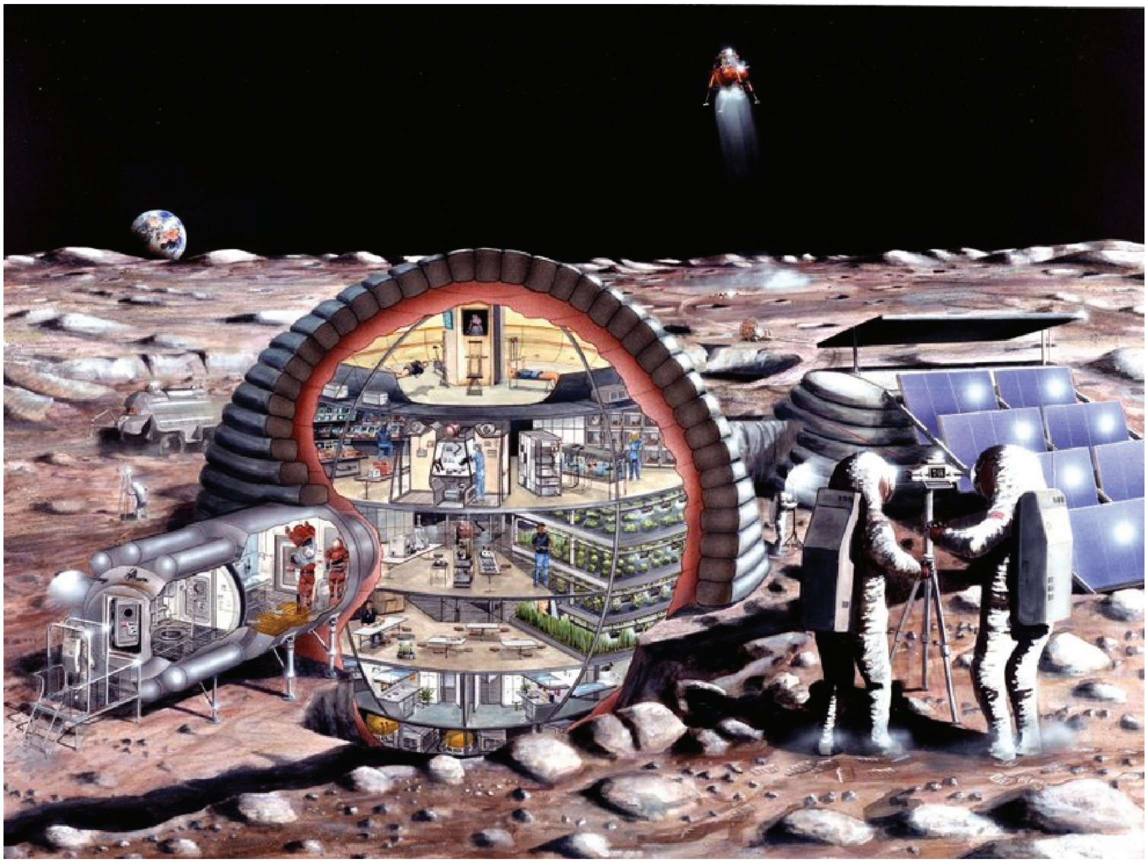
Several companies offer model rockets that could be used for this activity, ranging in price from $8.00–$13.00 when buying in bulk. Each rocket should have a payload section just under one inch in diameter. Skill Level 1 rockets are recommended for students and teachers who are building model rockets for the first time or if the class is on a tight time frame.

Apogee. (n.d.). *Dynamo*. Retrieved January 16, 2009, from <http://www.apogeerockets.com/dynamo.asp>.

Estes. (n.d.). *Rockets*. Retrieved January 16, 2009, from <http://www.estesrockets.com/index.php#>.

Quest. (n.d.). *The outfitter for aerospace education*. Retrieved January 16, 2009, from <http://www.questaerospace.com/>.

Example of Potential Lunar Concrete Structures



Jernigan, M. (2006). *Challenges for humans living off Earth* (Presentation to ITEA Human Exploration Project Authors, November 2007, at Johnson Space Center). Houston, TX.

Pneumatic Structures

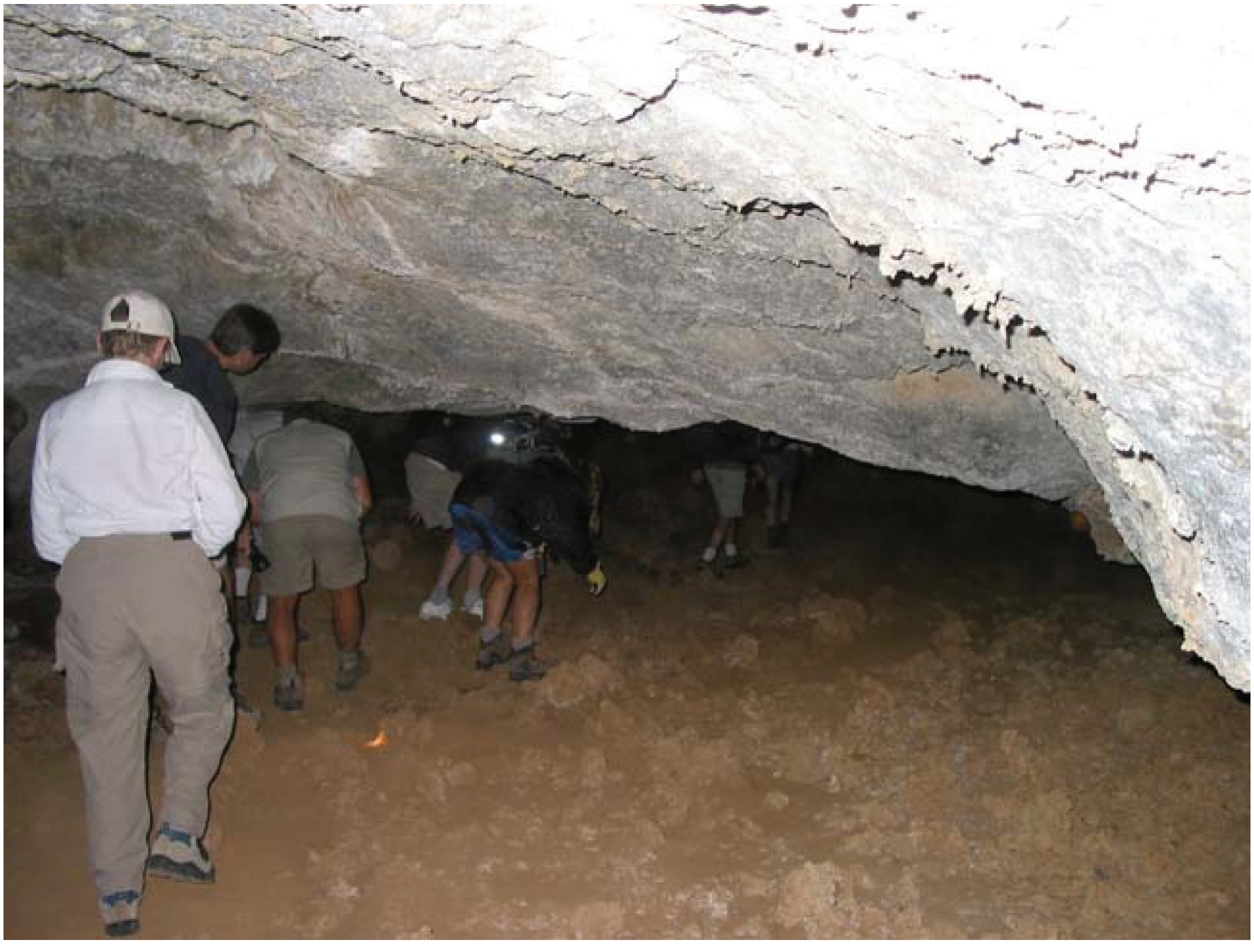
NASA has included the idea of inflatable structures as a viable option for lunar and Mars habitats. Students should be required to review the brief description and images below and continue a more comprehensive investigation into this concept. Students should locate as many NASA-sponsored contractors, research institutions, or facilities as possible, such as Marshall and Glenn, to see how far design concepts have evolved.

Robert (Bob) Zubrin, an American aerospace engineer, has been very interested in NASA's TransHab version, originally brainstormed as an add-on habitat module for the International Space Station. Bob saw it at once as a faster, better, cheaper MarsHab both for the crew in transit and for use on Mars itself.

NASA. (2003). *TransHab concept*. Retrieved January 16, 2009, from <http://spaceflight.nasa.gov/history/station/transhab/>.

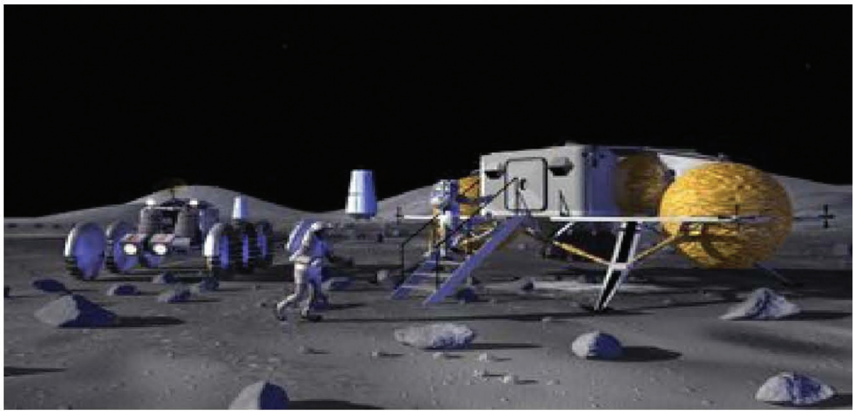
Note that in NASA's version, designed for unshielded use in open space, the inflatable envelope wall is a foot thick and many-layered to provide micrometeorite protection. This would not be necessary for a surface version, which is to be covered promptly with regolith shielding. The thick wall of the NASA version is the reason for the relatively small size of TransHab. With a thinner wall designed to hold pressure only, the size of the inflatable torus can be quite a bit larger.

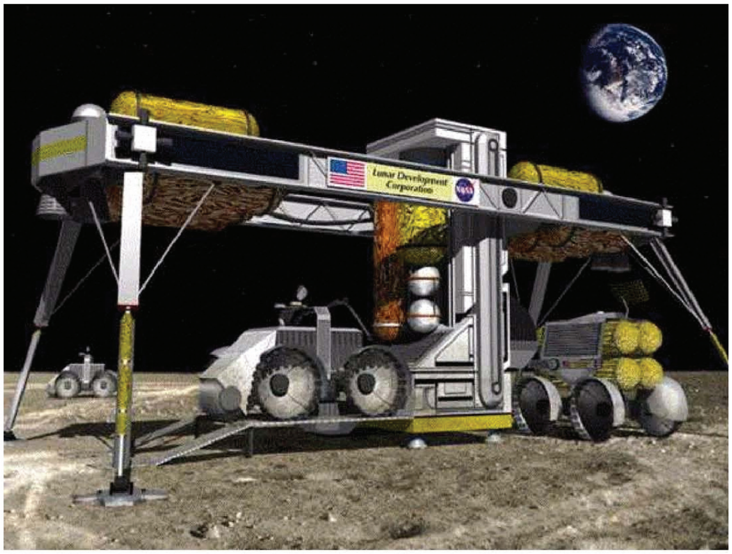
Lavatubes Example on Earth

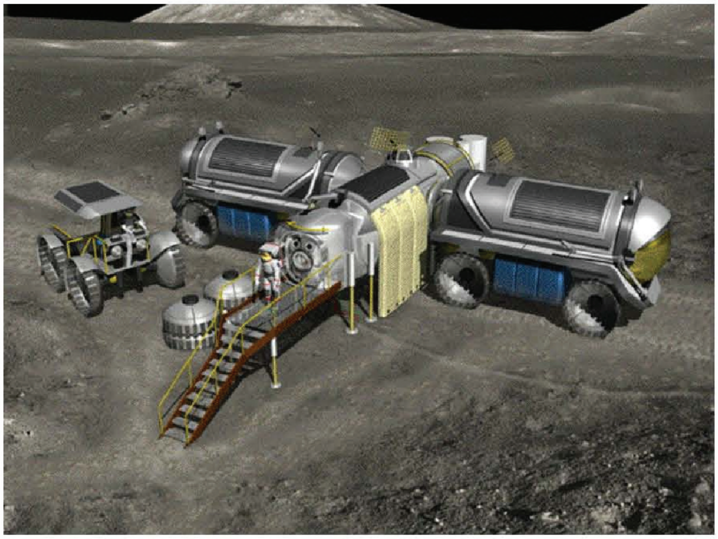


NASA. (2003). *Introduction to planetary science: Lava tube*. Retrieved January 16, 2009, from <http://nai.arc.nasa.gov/insight/insight_albums/5/>.

Steel Frame and Modular Structure







Gruener, J. E. (2006). *Lunar exporation* (Presentation to ITEA Human Exploration Project Authors, November 2006, at Johnson Space Center). Houston, TX.

Technology Readiness Levels

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Introduction

Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The TRL approach has been used on and off in NASA space technology planning for many years and was recently incorporated in the NASA Management Instruction (NMI 7100) addressing integrated technology planning at NASA. The most useful the general model must include the following:

(a) "Basic" research in new technologies and concepts (targeting identified goals, but not necessarily specific systems).
(b) Focused technology development addressing specific technologies for one or more potential identified applications.
(c) Technology development and demonstration for each specific application before the beginning of full system development of that application.
(d) System development (through first unit fabrication).
(e) System "launch" and operations.

Technology Readiness Levels Summary

TRL 1	Basic principles
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground and space)
TRL 9	Actual system "flight proven" through successful mission operations

Discussion of Each Level

The following paragraphs provide a descriptive discussion of each technology readiness level, including an example of the type of activities that would characterize each TRL.

TRL 1

Basic principles observed and reported

This is the lowest "level" of technology maturation. At this level, scientific research begins to be translated into applied research and development. Examples might include studies of basic properties of materials (e.g., tensile strength as a function of temperature for a new fiber).

Cost to Achieve: Very Low "Unique" Cost (investment cost is borne by scientific research programs)

TRL 2

Technology concept and/or application formulated

Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be "invented" or identified. For example, following the observation of High Critical Temperature (HTC) superconductivity, potential applications of the new material for thin film devices (e.g., SIS mixers) and in instrument systems (e.g., telescope sensors can be defined). At this level, the application is still speculative; there is not experimental proof or detailed analysis to support the conjecture.

Cost to Achieve: Very Low "Unique" Cost (investment cost is borne by scientific research programs)

TRL 3

Analytical and experimental critical function and/or characteristic proof-of-concept

At this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2. For example, a concept for High Energy Density Matter (HEDM) propulsion might depend on slush or super-cooled hydrogen as a propellant: TRL 3 might be attained when the concept-enabling phase/temperature/pressure for the fluid was achieved in a laboratory.

Cost to Achieve: Low "Unique" Cost (investment cost is borne by scientific research programs)

TRL 4

Component and/or breadboard validation in laboratory environment

Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is relatively "low-fidelity" compared to the eventual system; it could be composed of ad hoc discrete components in a laboratory. For example, a TRL 4 demonstration of a new "fuzzy logic" approach to avionics might consist of testing the algorithms in a partially computer-based, partially bench-top component (e.g., fiber optic gyros) demonstration in a controls lab using simulated vehicle inputs.

Cost to Achieve: Low-to-moderate "Unique" Cost (investment will be technology specific, but probably several factors greater than investment required for TRL 3)

TRL 5

Component and/or breadboard validation in relevant environment

At this, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, subsystem-level, or system-level) can be tested in a "simulated" or somewhat realistic environment. From one to several new technologies might be involved in the demonstration. For example, a new type of solar photovoltaic material promising higher efficiencies would at this level be used in an actual fabricated solar array "blanket" that would be integrated with power supplies, supporting structure, etc., and tested in a thermal vacuum chamber with solar simulation capability.

Cost to Achieve: Moderate "Unique" Cost (investment will be technology dependent, but likely to be several factors greater than cost to achieve TRL 4)

TRL 6

System/subsystem model or prototype demonstration in a relevant environment (ground or space)

A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system—which would go well beyond ad hoc, "patch-cord," or discrete component level breadboarding—would be tested in a relevant environment. At this level, if the only "relevant environment" is the environment of space, then the model/prototype must be demonstrated in space. Of course, the demonstration should be successful to represent a true TRL 6. Not all technologies will undergo a TRL 6 demonstration; at this point the maturation step is driven more by assuring management confidence than by R&D requirements. The demonstration might represent an actual system application, or it might only be similar to the planned application, but using the same technologies. At this level, several-to-many new technologies might be integrated into the demonstration. For example, an innovative approach to high temperature/low mass radiators, involving liquid droplets and composite materials, would be demonstrated to TRL 6 by actually flying a working, subscale (but scaleable) model of the system on a Space Shuttle or International Space Station "pallet." In this example, the reason space is the "relevant" environment is that microgravity plus vacuum plus thermal environment effects will dictate the success/failure of the system–and the only way to validate the technology is in space.

Cost to Achieve: Technology and demonstration specific; a fraction of TRL 7 if on ground; nearly the same if space is required

TRL 7

System prototype demonstration in a space environment

TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. It has not always been implemented in the past. In this case, the prototype should be near or at the scale of the planned operations system, and the demonstration must take place in space. The driving purposes for achieving this level of maturity are to assure system engineering and development management confidence (more than for purposes of technology R&D). Therefore, the demonstration must be of a prototype of that application. Not all technologies in all systems will go to this level. TRL 7 would normally only be performed in cases where the technology and/or subsystem application is mission critical and relatively high risk. Example: The Mars Pathfinder Rover is a TRL 7 technology demonstration for future Mars microrovers based on that system design. Example: X-vehicles are TRL 7, as are the demonstration projects planned in the New Millennium spacecraft program.

Cost to Achieve: Technology and demonstration specific, but a significant fraction of the cost of TRL 8 (investment = "Phase C/D to TFU" for demonstration system)

TRL 8

Actual system completed and "flight qualified" through test and demonstration (ground or space)

By definition, all technologies being applied in actual systems go through TRL 8. In almost all cases, this level is the end of true "system development" for most technology elements. Example: This would include DDT&E through Theoretical First Unit (TFU) for a new reusable launch vehicle. This might include integration of new technology into an existing system. Example: loading and testing successfully a new control algorithm into the onboard computer on Hubble Space Telescope while in orbit.

Cost to Achieve: Mission specific; typically highest unique cost for a new technology (investment = "Phase C/D to TFU" for actual system)

TRL 9

Actual system "flight proven" through successful mission operations

By definition, all technologies being applied in actual systems go through TRL 9. In almost all cases, the end of last "bug fixing" aspects of true "system development;" for example, small fixes/changes to address problems found following launch (through "30 days" or some related date). This might include integration of new technology into an existing system (such as operating a new artificial intelligence tool into operational mission control at JSC). This TRL does not include planned product improvement of ongoing or reusable systems. For example, a new engine for an existing RLV would not start at TRL 9; such "technology" upgrades would start at the appropriate level in the TRL system.

Cost to Achieve: Mission specific; less than cost of TRL 8 (e.g., cost of launch, plus 30 days of mission operations)

Two additional terms need to be introduced and explored by students in order to gain a comprehensive overview of NASA project management techniques. These terms are:

- Pull and push technology development
- Push technology development

Pull technologies are developed in response to an immediate need. Given this urgency, the tendency is to avoid extensive dependence on innovation and rather to adapt existing, mature technologies by incorporating the minor modifications required for the application niche. By definition, the customer is fully prepared to cover all costs associated with the development, and the outcome has a high probability of success.

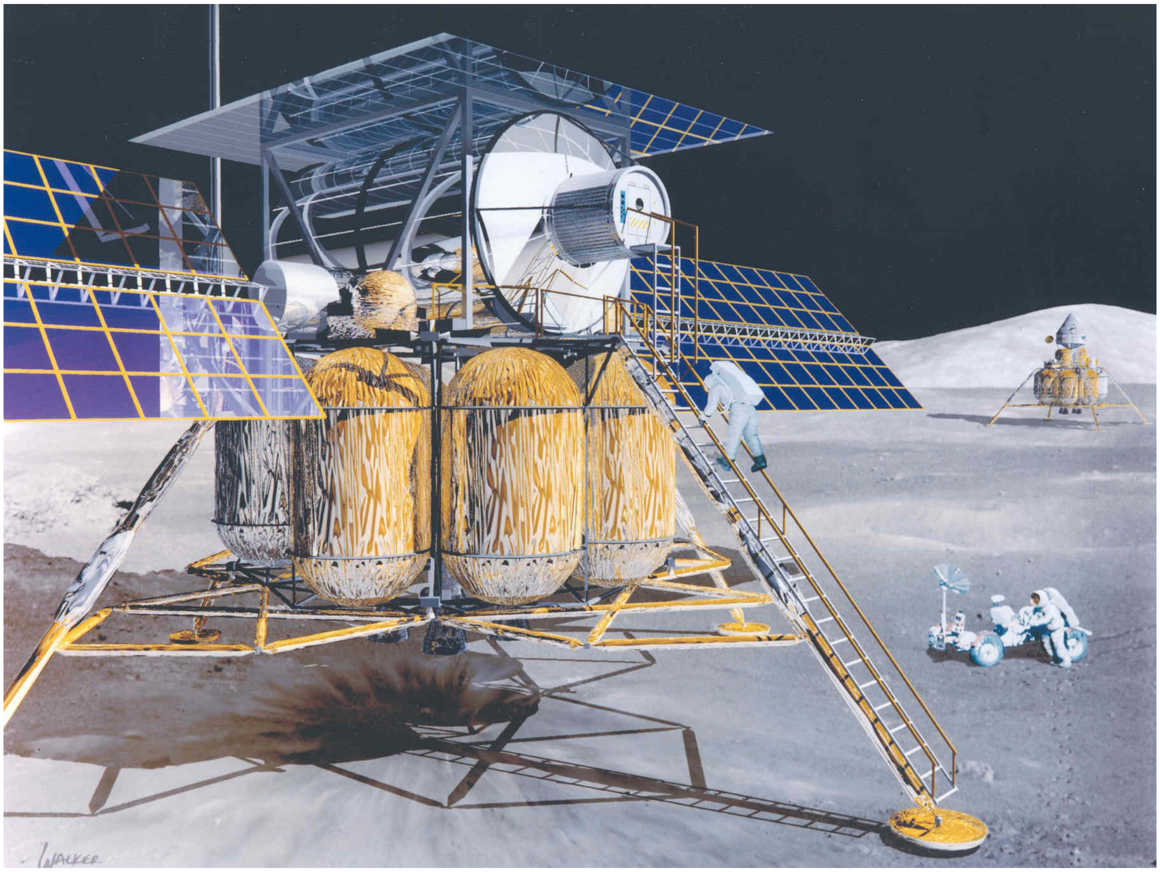
Push technologies, on the other hand, are "disruptive" and are based almost exclusively on the innovator's vision of customers' perceived needs. On the plus side, this type of development carries the promise of a pioneering effort. The downside, however, is that most often the outcome has a low probability of success.

In a few cases, this high failure rate could be attributed to unforeseen, technical "fatal flaws." Most of the failures are due to the inability of the technology development to cross the TRL gap to become a "pull" technology. The causes of failure are peculiar to each case, but, in general, are a combination of unenthusiastic customer perceptions, impedance mismatch with customer needs, bad timing, insufficient niche development, and a lack of necessary technological support infrastructure, among other reasons.

The end result of the TRL gap is that the infusion of advanced technology is slowed, and in some cases, stopped. Therefore, the TRL gap problem can be reformulated as the challenge of how to efficiently transition push technologies into pull technologies.

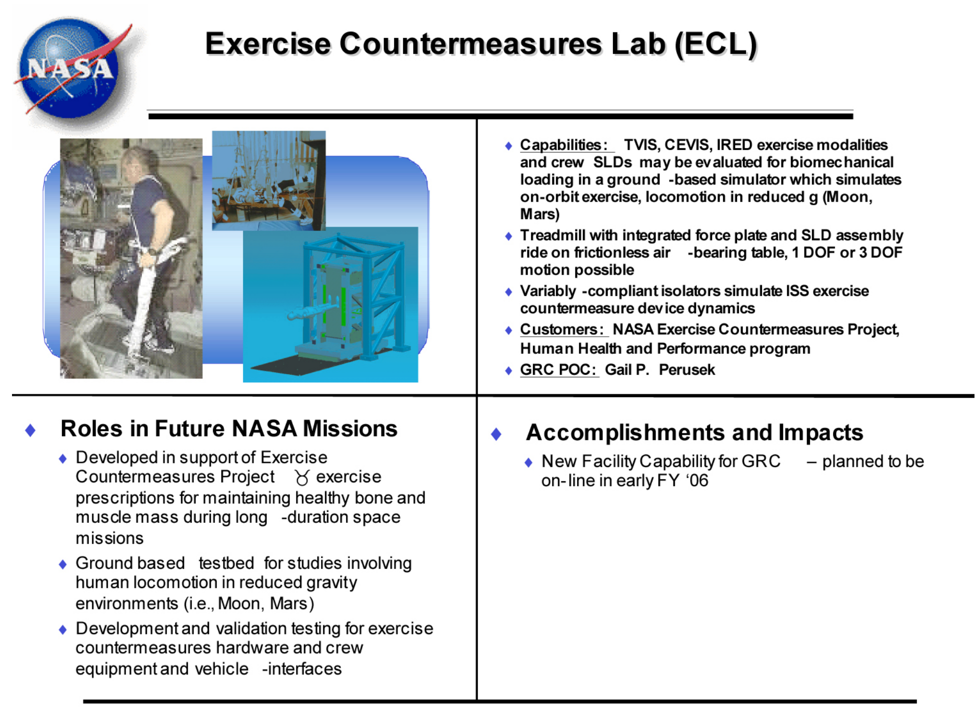
Artist’s Rendition of First Lunar Outpost

Power System: Sun Tracking Arrays and Regenerative Fuel Cells



Gruener, J. E. (2006). *Lunar exporation* (Presentation to ITEA Human Exploration Project Authors, November 2006, at Johnson Space Center). Houston, TX.

Exercise Countermeasures Laboratory (ECL)



Exercise Countermeasures Lab (ECL)

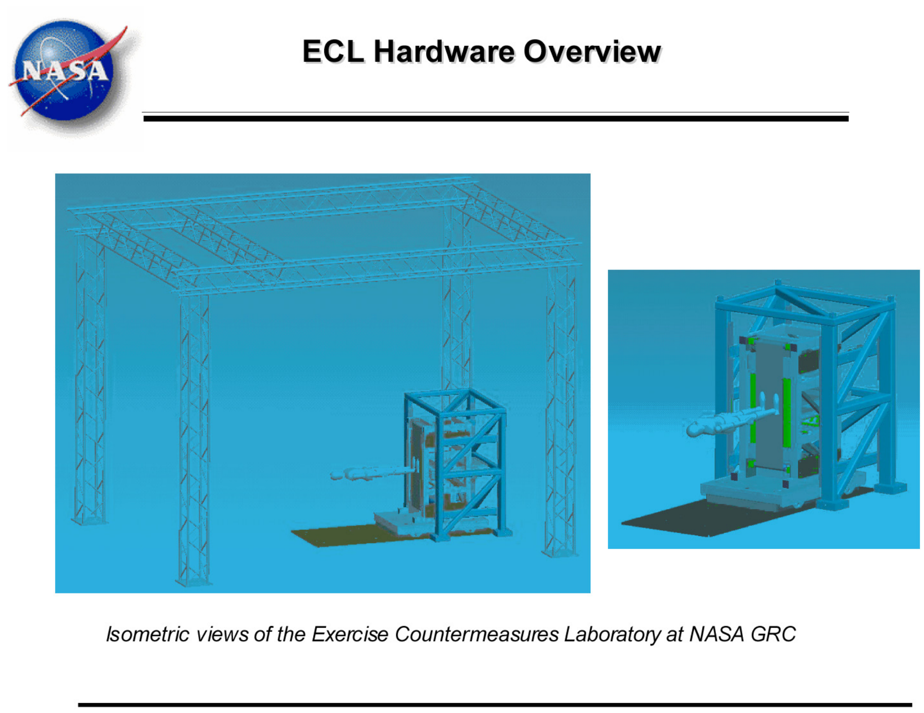
- **Capabilities:** TVIS, CEVIS, IRED exercise modalities and crew SLDs may be evaluated for biomechanical loading in a ground-based simulator which simulates on-orbit exercise, locomotion in reduced g (Moon, Mars)
- **Treadmill with integrated force plate and SLD assembly ride on frictionless air-bearing table, 1 DOF or 3 DOF motion possible**
- **Variably-compliant isolators simulate ISS exercise countermeasure device dynamics**
- **Customers:** NASA Exercise Countermeasures Project, Human Health and Performance program
- **GRC POC:** Gail P. Perusek

Roles in Future NASA Missions

- Developed in support of Exercise Countermeasures Project ♉ exercise prescriptions for maintaining healthy bone and muscle mass during long-duration space missions
- Ground based testbed for studies involving human locomotion in reduced gravity environments (i.e., Moon, Mars)
- Development and validation testing for exercise countermeasures hardware and crew equipment and vehicle-interfaces

Accomplishments and Impacts

- New Facility Capability for GRC – planned to be on-line in early FY '06



ECL Hardware Overview

Isometric views of the Exercise Countermeasures Laboratory at NASA GRC

NASA. (2006). *ECL quad chart and general information* (Presentation to ITEA Human Exploration Project Authors, November 2006, at Glenn Research Center). Brooke Park, OH.

Power System Applications

(Based on Past Studies)

• Spacecraft housekeeping power	10–30 kW
• Piloted transfer vehicle	30–50 kW
• NEP planetary probes	100–300 kW
• NEP cargo transfer vehicle	500–1000 kW
• Piloted NEP	5–20 MW
• Planetary rovers	
- Robotic	1–3 kW
- LRV type	1–3 kW
- Pressurized	10–20 kW
- Construction/mining	20–50 kW
• Planetary outpost	30–50 kW
• Planetary base (several Habs & ISRU)	150–500 kW

Cataldo, R. (2006). *Overview of planetary power system options for education* (Presentation to ITEA Human Exploration Project Authors, November 2006, at Glenn Research Center). Brooke Park, OH.

NASA Developing Fission Surface Power Technology

NASA astronauts will need power sources when they return to the Moon and establish a lunar outpost. NASA engineers are exploring the possibility of nuclear fission to provide the necessary power and taking initial steps toward a nonnuclear technology demonstration of this type of system.

A fission surface power system on the Moon has the potential to generate a steady 40 kW of electric power, enough for about eight houses on Earth. It works by splitting uranium atoms in a reactor to generate heat that then is converted into electric power. The fission surface power system can produce large amounts of power in harsh environments, like those on the surface of the Moon or Mars, because it does not rely on sunlight. The primary components of fission surface power systems are a heat source, power conversion, heat rejection and power conditioning, and distribution.

“Our goal is to build a technology demonstration unit with all the major components of a fission surface power system and conduct nonnuclear, integrated system testing in a ground-based space simulation facility,” said Lee Mason, principal investigator for the test at NASA’s Glenn Center in Cleveland. “Our long-term goal is to demonstrate technical readiness early in the next decade, when NASA is expected to decide on the type of power system to be used on the lunar surface.”

Glenn recently contracted for the design and analysis of two different types of advanced power conversion units as an early step in the development of a full system-level technology demonstration. These power conversion units are necessary to process the heat produced by the nuclear reactor and efficiently convert it to electrical power.

The first design concept by Sunpower, Inc. of Athens, Ohio, uses two opposed piston engines coupled to alternators that produce 6 kW each, or a total of 12 kW of power. The second contract with Barber Nichols, Inc. of Arvada, Colorado, is for development of a closed Brayton cycle engine that uses a high-speed turbine and compressor coupled to a rotary alternator that also generates 12 kW of power.

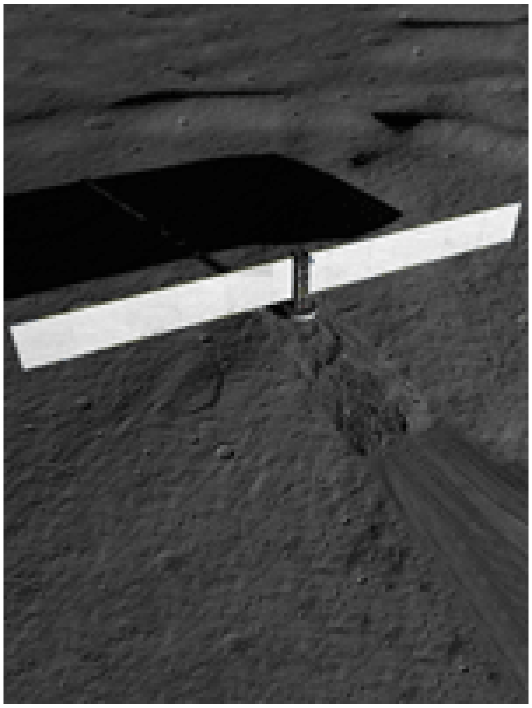
“Development and testing of the power conversion unit will be a key factor in demonstrating the readiness of fission surface power technology and provide NASA with viable and cost-effective options for nuclear power on the Moon and Mars,” said Don Palac, manager of Glenn’s Fission Surface Power Project.

After a one-year design-and-analysis phase, a single contractor will be selected to build and test a prototype power conversion unit. When complete, the power conversion unit will be integrated with the other technology demonstration unit’s major components. Glenn will develop the heat rejection system and provide the space simulation facility. Glenn also will work in conjunction with the Department of Energy and NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama. MSFC will develop and provide a nonnuclear reactor simulator with liquid metal coolant as the heat source unit for the technology demonstration.

A nuclear reactor used in space is much different than Earth-based systems. There are no large concrete cooling towers, and the reactor is about the size of an office trash can. The energy produced from a space reactor also is much smaller but more than adequate for the projected power needs of a lunar outpost.

Testing of the nonnuclear system is expected to take place at Glenn in 2012 or 2013. These tests will help verify system performance projections, develop safe and reliable control methods, gain valuable operating experience, and reduce technology and programmatic risks. This technology demonstration is being conducted as part of NASA’s Exploration Technology Development Program.

An Artist's Concept of a Fission Surface Power System on the Surface of the Moon



NASA. (2008). *NASA developing fission surface power technology*. Retrieved January 16, 2009, from <http://www.nasa.gov/home/hqnews/2008/sep/HQ_08-227_Moon_Power.html>.

Lighting up the Lunar Night with Fuel Cells

How do you survive in a remote, mountainous region that has no water or wind and sometimes goes without sunlight for weeks?

This is not the premise for a survivalist reality show; it's a question NASA must answer before sending humans to live and work on the Moon.

Within the next twenty years, people again will explore the vast lunar terrain. This time, we're going to build a permanent outpost where we will conduct scientific research, learn to live off the land, and test new technologies for future missions to Mars and beyond.

During the day, solar arrays will generate electricity for habitats, life support systems, rovers, communications systems, and other equipment. But lunar nights last up to 334 hours in some places. Even at the Moon's south pole, the sun never rises high. Mountains and hills block sunlight from reaching the surface, and night bathes the Moon in total darkness for more than 100 hours.

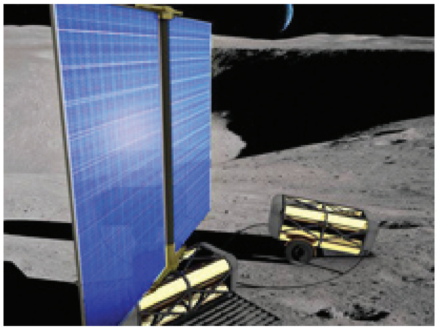


Illustration of a solar array and regenerative fuel cell on the Moon. Credit: NASA.

NASA's Glenn Research Center in Cleveland is leading an effort to develop systems that could store energy for use during the long, frigid lunar nights. The solution may be a fuel cell system that originally was designed for a high-altitude solar-electric airplane.

In 2005, Electrical Engineer David Bents and his team at Glenn demonstrated the first and only fully closed-loop, regenerative fuel cell ever operated. Though the technology never was implemented on the airplane, Glenn engineers are gleaning valuable information from the project as they design a next-generation regenerative fuel cell for the Moon.

How It Works:

A typical hydrogen fuel cell combines hydrogen from a tank and oxygen from the air to produce electricity, leaving water and heat as its only byproducts. A regenerative fuel cell also works in reverse, using electricity to divide the water into hydrogen and oxygen, which are fed back into the fuel cell to produce more electricity.

"What makes our regenerative fuel cell unique is that it's closed loop and completely sealed," Bents said. "Nothing goes in and nothing comes out, other than electrical power and waste heat. The hydrogen, oxygen, and product water inside are simply recycled over and over again."

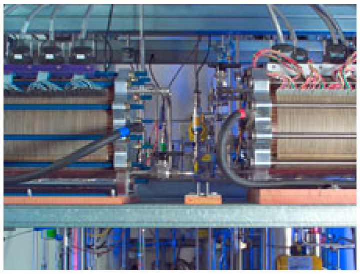
In other words, instead of using oxygen from the air like other regenerative fuel cells, the closed-loop system reuses the oxygen extracted from the water. That makes it ideal for use on the Moon, where there is no oxygen.

"On the Moon, you would start with a tank of water. You'd use the solar arrays to make hydrogen and oxygen during the day, then use the hydrogen and oxygen to make electricity during the night when there's no sun," said Bents. "Ideally, if nothing broke and nothing wore out, it could run forever without being refueled."

The system is very similar to a rechargeable battery, but it can store four to six times more energy than a battery of the same weight.

An Energy Storage Milestone

In the summer of 2005, Glenn demonstrated the first fully closed-loop regenerative fuel cell ever operated. It completed five continuous day and night cycles. That's nowhere near forever, but at the end of the demonstration, it had not leaked and was capable of running at least one more cycle.



Regenerative fuel cell stacks at NASA Glenn. Credit: NASA

Those five days of operation were the result of several years of hard work. The team's diligence paid off by proving a regenerative fuel cell's potential as an energy storage device for aerospace solar power systems.

Since the demonstration in 2005, the team has modified and upgraded much of the software, circuitry, and hardware to make the system run more reliably.

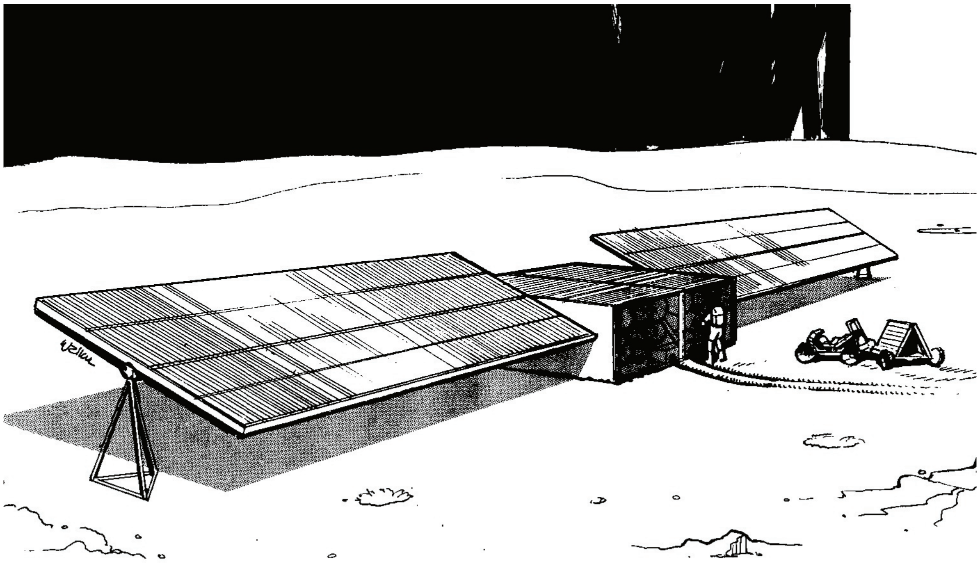
The lessons they learned and information they gathered in the process will be invaluable to Glenn's Energy Storage Project Office when it develops a prototype system to work in the harsh lunar environment.

"Even though it was originally designed for an airplane, the system has given us a leg up," said Ann Over, chief of Glenn's Advanced Capabilities Project Office. "The knowledge we gained will feed directly into our lunar regenerative fuel cell technology program."

NASA. (2007). *Lighting up the lunar night with fuel cells*. Retrieved January 16, 2009, from <http://www.nasa.gov/exploration/home/lunar_fuel_cell.html>.

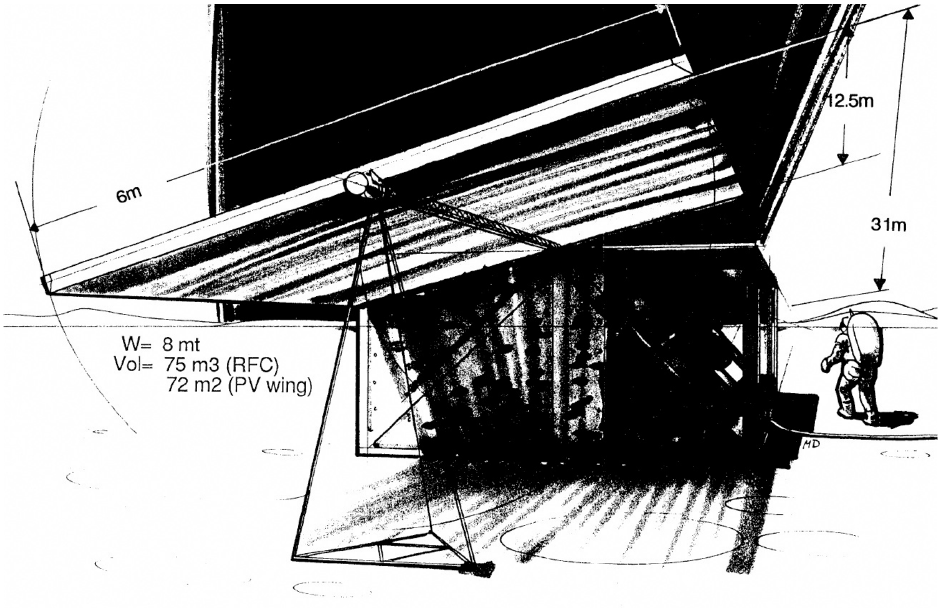
Solar Collectors

NASA 90-Day Study: Initial Capability



Power System (25/12.5kW)

90 Day Lunar/Mars Study



Power System (25/12.5kW)

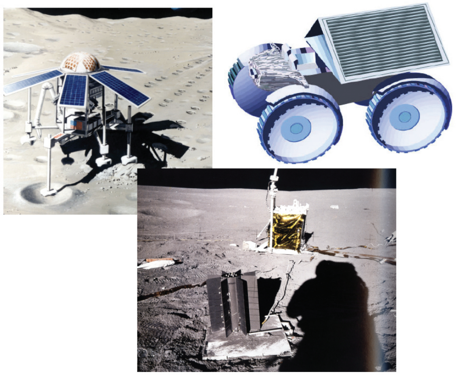
90 Day Lunar/Mars Study

Cataldo, R. (2006). *Overview of planetary power system options for education* (Presentation to ITEA Human Exploration Project Authors, November 2006, at Glenn Research Center). Brooke Park, OH.

Lunar Surface Power Evolution

2008

Low Power Science

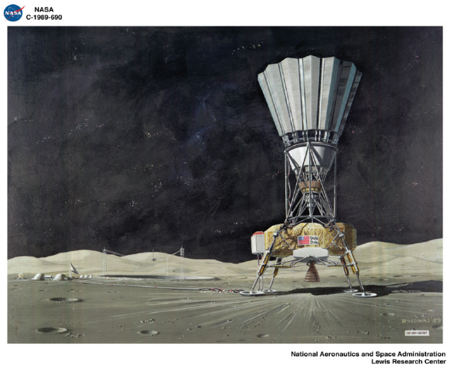


10s of Watts - few kWe

- Stationary Science
- Mobile Science Rover
- Mobile Power Cart

2015

High Power Science/Initial Human

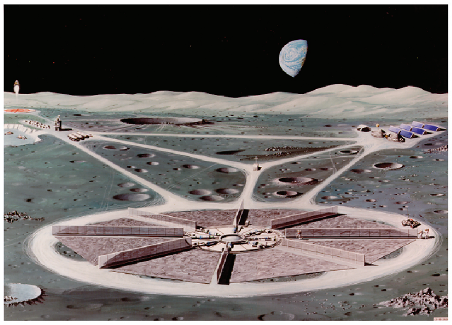


10s kWe - 100 kWe

- Initial Human Capability
- Mars Hardware Testbed
- Science Observatory/Human Outpost

2020

ISRU Lunar Capability



100s kWe - 1000 kWe

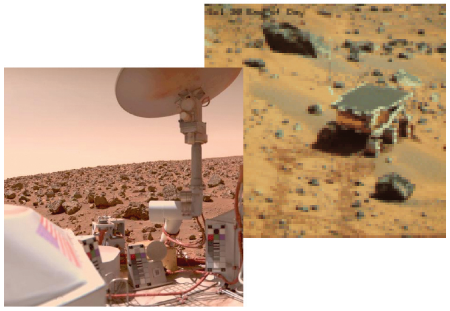
- Human Base Operations
- Lunar Oxygen Production
- Mars Base Testbed

Cataldo, R. (2006). *Overview of planetary power system options for education* (Presentation to ITEA Human Exploration Project Authors, November 2006, at Glenn Research Center). Brooke Park, OH.

Mars Surface Power Evolution

2008

Low Power Science



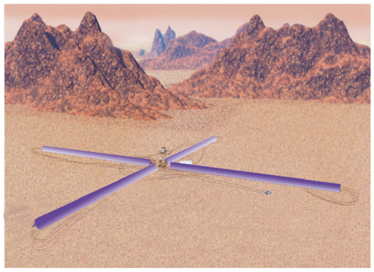
Solar or Isotope

10s of Watts - few kWe

- Stationary Science
- Mobile Science Rover
- Mobile Power Cart

2015

High Power Science/Initial Human



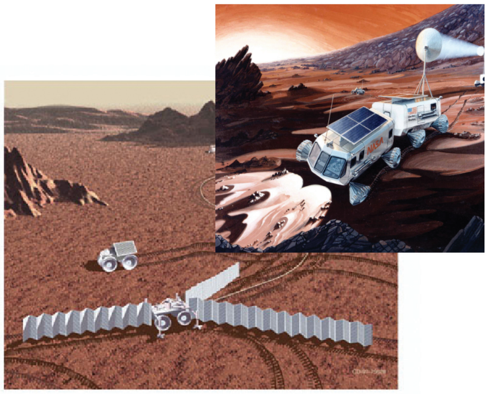
Solar

10-20 kWe

- 50 day Initial Human Stay
- Local Exploration Rover

2020

Base/ISRU Mars Capability



Nuclear

30s kWe - 200 kWe

- 500 day Base Operations
- Propellant Production
- Long Range Exploration rover
- Multi-site Visitation

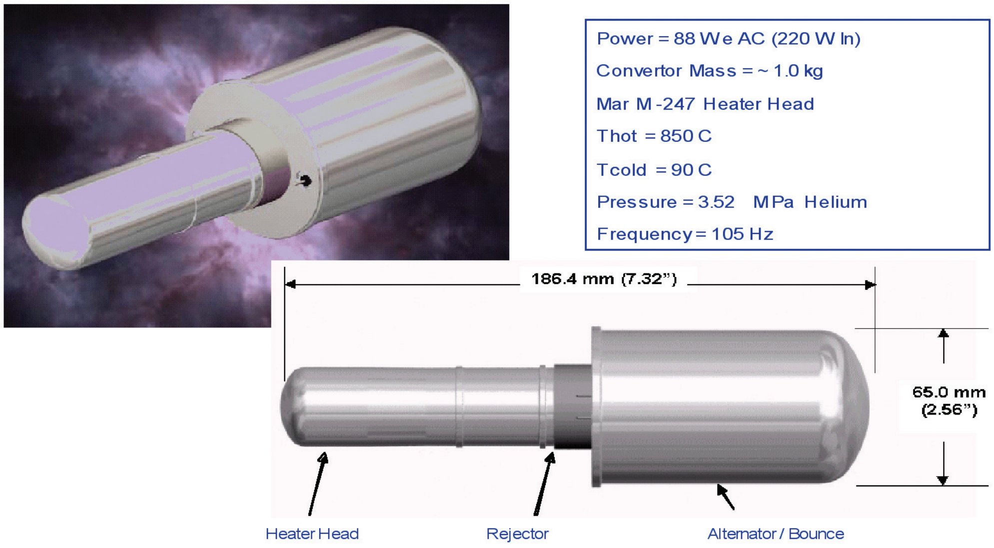
Cataldo, R. (2006). *Overview of planetary power system options for education* (Presentation to ITEA Human Exploration Project Authors, November 2006, at Glenn Research Center). Brooke Park, OH.

Lesson 2 Enrichment Activities

Enrichment Activity 1

Students can be challenged to investigate a cutting-edge technology for surface power generation. There are currently several organizations, including NASA, that are reviewing rather visionary concepts for power and propulsion. One of these is fusion reactors, and another interesting prospect is referred to as Advanced Radioisotope Thermoelectric Generators (RTGs). One example of such a generator is the Advanced Stirling Convertor shown below.

Advanced Stirling Convertor



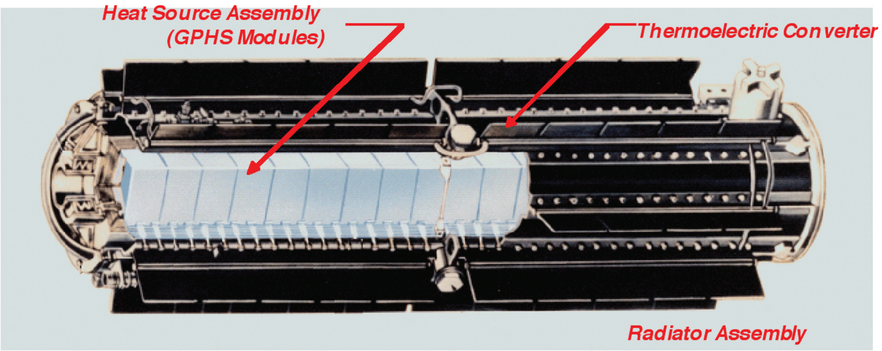
Power = 88 We AC (220 W In)
Convertor Mass = ~ 1.0 kg
Mar M-247 Heater Head
Thot = 850 C
Tcold = 90 C
Pressure = 3.52 MPa Helium
Frequency = 105 Hz

Based on student interest, the instructional team should offer these concepts for further review and reporting by individual or team efforts. A similar approach could be taken where students would investigate, prepare a multi-media presentation, and construct an authentic model and then share that as part of a class seminar led by them. This provides a powerful peer instruction event. The instructional team would facilitate and conduct assessments during this student-planned and coordinated seminar.

Another feature during class seminars is that student teams present clear images and supporting data through their discussions to ensure that all members of the class understand the differences between the various surface power technologies. Comparing these technologies can be accomplished by peer instruction with sufficient research, planning, and preparation for such presentations and discussions using images, such as the one below, to clearly describe key data for an RPS system using Plutonium 238 as fuel, and then compare this technology with similar data from other teams.

This approach can help students to not only refine their communication skills, but gain deeper understandings into sophisticated technologies.

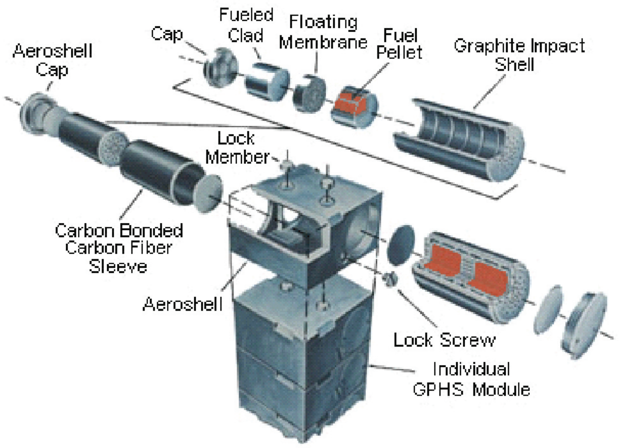
GPHS RTG – RPS SOA



- Converter: Solid state thermoelectric device containing 572 unicouples
- Heat Source: 18 GPHS modules
- Power: 292 We (BOL)
- Mass: 56 kg
- Efficiency: 6.8%
- Specific Power: 5.2 We/kg
- Life: >27 years of unicouple operation demonstrated in space
- Hot Side Temp: 1273 K
- Cold Side Temp: 573 K

Students should also use three-dimensional imaging software, such as Solidworks®, to generate assembly drawings, which can then be used in numerous visual materials to help explain sophisticated technologies, such as this exploded view of an RPS generator. Notice that key parts and subsystems are clearly shown as well as their relationship to the larger system. Also included is critical data that help to explain overall function along with performance for the entire technology.

GPHS – Thermal Building Block



- Each GPHS module contains four Ir-clad $^{238}PuO_2$ fuel pellets
- Each pellet contains ~150 g $^{238}PuO_2$ and generates ~62.5 W_{th} heat
- Iridium clad operation of 660 -1273 K to maintain ductility and limit grain growth

• Dimensions:	9.32 cm x 9.72 cm x 5.31 cm (≤ Cassini) 9.32 cm x 9.96 cm x 5.82 cm (enhanced)
• Mass:	1.45 kg (≤ Cassini) 1.60 kg (enhanced)
• Thermal Power:	~250 W_{th} (BOL)

Enrichment Activity 2

Another interesting investigation as enrichment for students is to challenge them to locate recent announcements by NASA that offer funding for further development of surface power generation systems that have been presented in this lesson or represent cutting-edge or emerging technologies. Students should review and then present these to the class and other appropriate audiences as part of a formal class seminar on surface power generation informational updates.

Enrichment Activity 3

The Rochester Institute of Technology has a Nanopower Research Laboratory in the College of Science that conducts research on the generation and storage or energy using nanostructured materials, especially photovoltaic, waste heat recovery, battery, and fuel cell technology. Students could be challenged to investigate the work being done at this school as well as other institutions or engineering organizations that have comprehensive research programs for surface power systems that could be used by NASA for lunar habitation.

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