HABITAT DESIGN OPTIMIZATION AND ANALYSIS

Michael P. SanSoucie[1], Patrick V. Hull[1], and Michael L. Tinker[2]

[1]Jacobs Sverdrup, Huntsville, AL 35812.

[2]NASA Marshall Space Flight Center, Spacecraft & Vehicle Systems Dept, Project Integration & Requirements Branch / EV11, Marshall Space Flight Center, AL 35812.

Address correspondence to Michael P. SanSoucie, Jacobs Sverdrup, ESTS Group, Huntsville, AL 35812.
Tel: (256) 544-6539; Email: Michael.P.Sansoucie@nasa.gov

ABSTRACT

Long-duration surface missions to the Moon and Mars will require habitats for the astronauts. The materials chosen for the habitat walls play a direct role in the protection against the harsh environments found on the surface. Choosing the best materials, their configuration, and the amount required is extremely difficult due to the immense size of the design region. Advanced optimization techniques are necessary for habitat wall design. Standard optimization techniques are not suitable for problems with such large search spaces; therefore, a habitat design optimization tool utilizing genetic algorithms has been developed. Genetic algorithms use a "survival of the fittest" philosophy, where the most fit individuals are more likely to survive and reproduce. This habitat design optimization tool is a multi-objective formulation of structural analysis, heat loss, radiation protection, and meteoroid protection. This paper presents the research and development of this tool.

Keywords: lunar habitat, design, optimization, analysis

INTRODUCTION

The nation's Vision for Space Exploration calls for a human return to the Moon by 2020 and a later potential human mission to Mars. These future missions are expected to involve much more impressive activities than those of the Apollo program. Some missions may last several months, while others may last up to 600 days (1). These long duration surface missions require large outposts to accommodate living quarters (habitats) for the astronauts as well as indoor laboratory facilities. Transporting the materials required to build the necessary habitats is expensive (2). The greatest impediment to extended human presence on the Moon or Mars is the threat posed by the harsh environments found on their surfaces and in transit. The lunar environment is much different than the terrestrial environment; many of the load conditions on the Moon are extremely severe (2).

Crew habitats require impact resistance, thermal insulation, radiation protection, and structural support. The materials chosen for the habitat walls play a direct role in protection against each of the mentioned hazards. The cost of launching payload from Earth is approximately $10,000 per pound. Through the use of in-situ resources and terrestrial materials a habitat can be designed to protect against the hazards on the surface of the Moon and Mars.

Choosing the best materials, their configuration, and the amount required is extremely difficult due to the immense size of the design region. Clearly some sort of optimization method would be extremely beneficial.

OPTIMIZATION

There are several optimization techniques that could be used, each having a number of advantages and disadvantages. Standard optimization techniques such as hill climbing, Newton's method, etc., are not suitable for problems with the large search space that will be encountered when designing a surface habitat, because they seek only local optima (3).

Genetic algorithms are search algorithms based on the principles of evolution and natural genetics. They use a "survival of the fittest" philosophy, where the fittest individual is most likely to survive and reproduce, therefore transmitting its genes to the next generation (4). Genetic operators – crossover and mutation – are used to create the succeeding generation from the members (strings) of the current population. Each individual is assigned a fitness value based on how well it

satisfies the objective function, which is generated through engineering analysis of the candidate design. The probability of a design being propagated to the next generation as well as the frequency of occurrence of the design in the next generation is directly proportional to the fitness of the individual (3).

BACKGROUND

Objective

The purpose of this work is to develop a cross-disciplinary surface habitat optimization and analysis tool that can determine the best combination of chosen materials for the walls of a surface habitat. The tool optimizes the habitat materials for minimum upmass including the analysis of thermal losses and gains, structural integrity, meteoroid impact, radiation shielding, and material upmass. A pictorial depicting the various objectives is shown in Figure 1.

Meteoroid Impact

A meteoroid is a "naturally occurring solid body, traveling through space, which is too small to be called an asteroid or a comet" (5). It is estimated that meteoroids of approximately milligram mass strike lunar structures yearly. Velocities of meteoroids at the moon range from 13-18 km/s. Meteoroids of about 10^{-6} g can generate craters of 500μm in metals. The impacts of larger meteoroids are rarer; however, they pose a more significant threat. A meteoroid with a mass of about 1g can produce a crater of centimeter scale in metals (5).

Thermal

The thermal stability of a lunar habitat is of extreme importance. A lunar habitat experiences drastic thermal cycling loads during a lunar day. Temperature ranges can vary 200K on the surface of the moon; therefore, it is necessary to design a structure that can sustain such dramatic thermal cycling loads. Active heating and cooling is required for lunar habitats and a reduction of such a need will reduce the upmass of the required equipment. Therefore, thermal losses are calculated to determine the suitability of a given design.

Structural

Structural integrity of the lunar habitat is necessary to ensure that the habitat will remain intact. A lunar habitat must be able to withstand the residual loads from the habitat itself and the pressure differential of the "shirt sleeve" environment and the vacuum of space. All of these loads are considered when evaluating the structural integrity of the lunar habitat. A safety factor of 1.1 of the yield strength was used to analyze a loaded habitat.

Radiation

The radiation environment found in interplanetary space consists primarily of energetic ions and the galactic cosmic rays (GCR). Further sources of radiation are solar particle events (SPE). These are infrequent events that occur with large coronal mass ejections (CME) and result in a large amount of particles, mostly protons, moving through the solar system (6).

The presented habitat design tool calculates the dose equivalent on the inside of the habitat using simple material density and composition correlations.

Materials Database

The materials database contains all the necessary material properties for each of the analysis modules. Currently there are 24 materials in the database including aluminum, polyethylene, Mylar, lunar regolith cement, polyetheretherketone (PEEK), stainless steel, Kevlar and glass composites, rubber, and ethylene-vinyl alcohol copolymer (EVOH).

CODE DEVELOPMENT

The code was written primarily in MATLAB. Each analysis module was written as a separate subroutine. The optimization code is a genetic algorithm written by the authors at NASA Marshall Space Flight Center.

Meteoroid Impact

The meteoroid impact analysis is centered on the Fish-Summers single plate penetration equation (7):

$$P = Km_p^{0.352} \rho_p^{0.167} (V_p \cos\beta)^{0.875} \qquad (1)$$

where P = depth of penetration (cm), K = material constant, m_p = mass of the projectile, ρ_p = density of the projectile, V_p = velocity of the projectile, and β = angle of impact.

The projectile density and velocity were assumed to be 0.5 g/cm^3 and 20 km/s, respectively. The velocity is conservative, and the density is an estimate. A zero degree angle of impact was used to be conservative.

The material constant can be approximated for each material with the following equation (8):

$$K = \frac{0.816}{\varepsilon^{1/18}\sqrt{\rho_T}}$$ (2)

where ε = percent elongation and ρ_T = target density.

The projectile mass was determined (9) to be 0.22g by iterating between Equation 3 and 4 (10):

$$F = c_0\{(c_1 m^{0.306} + c_2)^{-4.38} + c_3(m + c_4 m^2 + c_5 m^4)^{-0.36} + c^6(m + c_7 m^2)^{-0.85}\}$$ (3)

where F = number of particles/m^2/year of mass, m, or greater, and the constants are listed in Table I.

$$P_{NI} = e^{-F*A*t}$$ (4)

where PNI = probability of no impact, F = number of particles/m^2/year of mass, m, or greater, A = area (m^2), and t = time (years).

To be conservative, the area was calculated based on a 32m outer radius, 15 year time, and 95% probability of no impact.

Only the outside layer of the habitat wall was analyzed by the impact code. This was chosen, because averaging all of the material constants (K) for each layer of the multi-layered wall would have resulted in less accurate penetration depths than by only analyzing the outer layer. Furthermore, this forces a tough outer layer to protect the habitat, which is most realistic.

Thermal

Steady State Numerical Thermal Model

A significant amount of research has been done to develop an analytical model of the multi-layer insulation heat leak of the habitat. Analysis of the habitat begins by the application of the first law of thermodynamics to the control volume.

This is a passive system, which means that no additional heat comes in or is taken away by thermal control system. A depiction of this system is shown in Figure 2, and the corresponding energy balance equation is the following:

$$\dot{E}_{in} + \dot{E}_g + \dot{E}_{out} = \dot{E}_{st}$$ (5)

where $\dot{E}_{in}$ is the energy into the system from outside sources, $\dot{E}_{out}$ is the energy loss from the system. $\dot{E}_{g}$ is the thermal energy generation and $\dot{E}_{st}$ is the rate of energy stored within the system.

The core problem of cooling or heating lunar habitats is to combat the solar heating by direct and indirect means: directly from the sun and indirectly from lunar reflection. The effective radiation heat transfer equation for the sun on the habitat is the following:

$$Q_{radSun} = a \cdot A_{Hab} \cdot G_S \tag{6}$$

where a is absorbtivity, A_{Hab} is incident surface area of the habitat, and G_s is the solar constant.

The effective radiation from the habitat takes the form of:

$$Q_{radHab} = e \cdot \sigma \cdot A \cdot T_S{}^4 \tag{7}$$

where e is the emmissivity, σ is the Stephen-Boltzman constant, A is the surface area of the habitat, and T_s is the surface temperature of the habitat.

Calculation of the surface temperature of the habitat requires the determination of the roots of a forth degree polynomial. Equating the conduction and radiation heat transfer rates and the polynomial is shown in Equation 8.

$$
\begin{aligned}
Q_{Cond} &= Q_{Rad} \\
\frac{(T_S - T_i)}{R_{EQ}} &= Q_{TOT} - e\sigma A T_S{}^4 \\
(Q_{TOT})R_{EQ} &- e\sigma A T_S{}^4 R_{EQ} - T_S + T_i = 0 \\
Q &= \left[R_{EQ} e\sigma A T_S{}^4 \quad 0 \quad 0 \quad -T_S \quad (Q_{TOT})R_{EQ} + T_i \right]
\end{aligned}
\tag{8}
$$

Thermal Model

A finite element thermal model of the thermal behavior of the lunar habitat was created in ANSYS, and an example result is shown in Figure 3. The model uses steady state analysis for a 2D cross section of the habitat.

Structural

A structural model was created and written in ANSYS. This structural model includes all loading conditions including pressure differential, thermal loading, and material weight in a 1/6 g environment. An example ANSYS plot is shown in Figure 4.

Radiation

The radiation analysis is a rule-of-thumb, level-zero analysis. It converts the thickness of each layer into a corresponding thickness of aluminum and then calculates the dose equivalent in the middle of the habitat.

The 1989 Solar Maximum radiation environment is used in this analysis, because it is assumed to be a near-worst-case solar particle event. The radiation model only accounts for protons, but a 5 rem dose is added to account for any secondary neutrons created from the primary proton bombardment.

Materials Database

The materials database is contained as a matrix that is called when the tool is started. It contains all the necessary material properties required for each of the analysis modules.

Optimization

A genetic algorithm (GA) was written specifically for the lunar habitat wall optimization problem. This GA uses a combination of crossover, mutation, and attrition to search the design region for the lunar habitat optimization problem.

The design region is defined as the area containing all of the possible solutions to the given problem. A design region of this stature is difficult to search. For example a 3-layer habitat wall created from 20 possible materials all with varying thickness would have the following number of possible solutions:

$$(\text{number of layers}) * (\text{possible material types})^{(\text{possible thickness})} = 320^{\infty}.$$

However, a GA can successfully find a "good" solution within this range.

OBJECTIVE FUNCTION FORMULATION

The habitat optimization tool described in this report attempts to optimally combine several aspects pertinent to a winning lunar habitat design: provide meteoroid protection, minimize thermal losses, maintain structural integrity, and

provide radiation protection. Each of the mentioned measured parameters is independently calculated based on the material and geometric framework of the candidate habitat design. The difficulty lies in the weighting of the individual objectives in question. Should they all be weighted equally and how is equality measured? These questions must be addressed to fully optimize a realistic lunar habitat design.

The weightings of the objective functions are simply a subjective measure the designers ordered priority. It may be the choice of the designer to emphasize the minimization of the active thermal control required to maintain the "shirt sleeve" environment for the astronauts or the meteoroid and radiation protection. Regardless of the designers choice it is necessary to scale the objectives such that the weightings are initially equal. Recall the various objectives are measured in heat loss, deflection, penetration depth, and radiation dose. To equally weight these parameters a series of 60 analyses were performed, the objective constraint values were changed sequentially to equalize the differing objective parameters. The final values are listed in Table II.

These values are simply an equal weighting representation of the individual objectives. At this point the designer has the option of emphasizing a single objective over another. Examples of designer weighted objectives are given in the next section.

EXAMPLE

An example optimized habitat configuration is shown in Figure 5. This configuration was selected with the weightings listed in Table III. The result is a habitat created primarily from lunar cement. This is expected since there is such a high emphasis on upmass.

CONCLUSIONS

A cross-disciplinary surface habitat optimization and analysis tool has been developed that can determine the best combination of materials for the walls of a surface habitat. The tool optimizes the habitat materials for minimum upmass including the analysis of thermal losses and gains, structural integrity, meteoroid impact, and radiation shielding. The tool presented in this paper provides a preliminary optimized habitat to give a design team a starting point for more detailed engineering and analysis. The focus of the optimization can be changed by varying the weightings of each of the analysis constraints. This adds a great

deal of flexibility for the user and allows the design to be focused for each application.

There is an evident value in seeking optimal habitat wall configurations. An optimal wall will provide mass savings, radiation protection, impact protection, insure a reliable base for future missions, and provide a safe haven for astronauts against the harsh environment of the lunar surface.

ACKNOWLEGEMENTS

BIOGRAPHICAL SKETCHES

Michael P. SanSoucie

Michael P. SanSoucie received a MS in Mechanical Engineering from the University of Massachusetts – Amherst in 2004 and a BS in Mechanical Engineering from Worcester Polytechnic Institute in 2002. His expertise is in materials science and engineering, and he has recently just finished a one and a half year research position with USRA. Currently, Michael is working as a Mechanical/Composite Engineer for Jacobs Sverdrup at NASA Marshall Space Flight Center.

Patrick V. Hull

Patrick V. Hull received a PhD in mechanical engineering from Tennessee Technological University in 2004 with expertise in optimal mechanism and structural design using genetic algorithms. He recently finished a two year postdoctoral research position at Marshall Space Flight Center. Currently, he is working as a senior design engineer for Jacobs Sverdrup at MSFC.

REFERENCES

1. Hoffman, S.J.; Kaplan, D.I., editors. Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team. NASA Special Publication 6107. Lyndon B. Johnson Space Center, TX; 1997.

2. Happel, J.A. Indigenous materials for lunar construction. Applied Mechanics Review. vol. 46[6]:313-325; 1993.

3. Goldberg, D.E. Genetic Algorithms in Search, Optimization, and Machine Learning. Boston: Addison-Wesley Publishing; 1989.

4. Srinivas, M.; Patnaik, L.M. Genetic Algorithms: A Survey. Computer. 27[6]:17-26; 1994.

5. Vaniman, et al. The Lunar Environment. In: Heiken, G.; Vaniman, D.; French, B.M.; Schmitt, J, eds. Lunar Sourcebook: A User's Guide to the Moon. New York: Cambridge University Press; 1991.

6. Clowdsley, M.S.; De Angelis, G.; Badavi, F.F.; Wilson, J.W.; Singleterry, R.C.; Thibeault, S.A. Surface Environments for Exploration. Space Technology and Application International Forum (STAIF); 2003.

7. Hayashida, K.B.; Robinson, J.H. Single Wall Penetration Equations. NASA Technical Memorandum 103565. George C. Marshall Space Flight Center, AL; 1991.

8. Jex, D.W.; Adkinson, A.B.; English, J.E.; Linebaugh, C.E. Hypervelocity Impact Testing of Cables. NASA Technical Note D-7178; 1973.

9. Robinson, J.H. private communication; 2005.

10. Anderson, B.J., editor; Smith, R.E., compiler: Natural Orbital Environment Definition Guidelines for Use in Aerospace Vehicle Development. NASA Technical Memorandum 4527. George C. Marshall Space Flight Center, AL; 1994.

TABLES

Table I. Constants for Equation 3.

Constant	Value
c_0	3.156×10^7
c_1	2.2×103
c_2	15
c_3	1.3×10^{-9}
c_4	10^{11}
c_5	10^{27}
c_6	1.3×10^{-16}
c_7	10^6

Table II: Final equally scaled constraint factors.

Constraint	Equation	Constraint Factor
Upmass	upmass*upmass_factor	1
Heat Loss	Q*thermal_factor	11.68
Structural	(δ + sf)*structural_factor	872227.76
Penetration Depth	P*penetration_factor	95233.43
Radiation Dose	Rem*radiation_factor	51064.29

Table III: Weightings for example optimization.

Constraint	Weighting
Upmass	6
Heat Loss	0.3
Deflection	0.1
Penetration Depth	0.3
Radiation Dose	0.3

FIGURES

| Thermal Losses | Structural Integrity | Upmass | Meteoroid Impact | Radiation Dose |
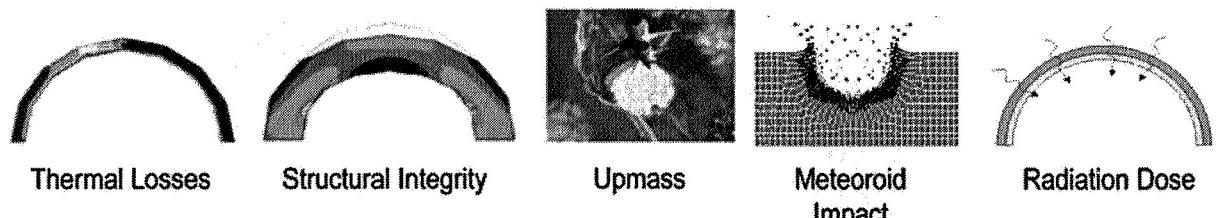
Figure 1: Multi-objective parameters for the lunar habitat design tool.

$\dot{E}_{in}$ $\dot{E}_g$ $\dot{E}_{st}$ $\dot{E}_{out}$
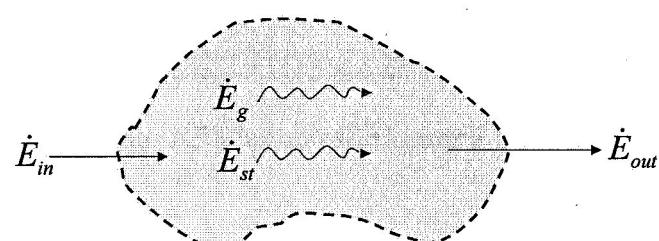
Figure 2: Theoretical control volume of the system.
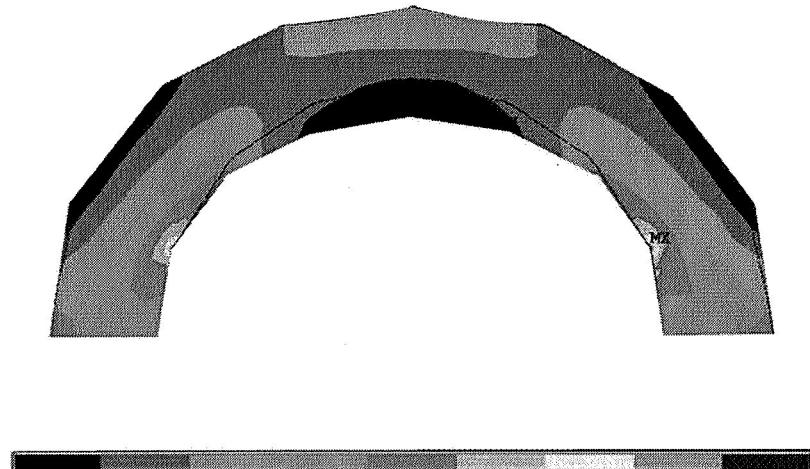
Figure 3: Example FEA thermal model.
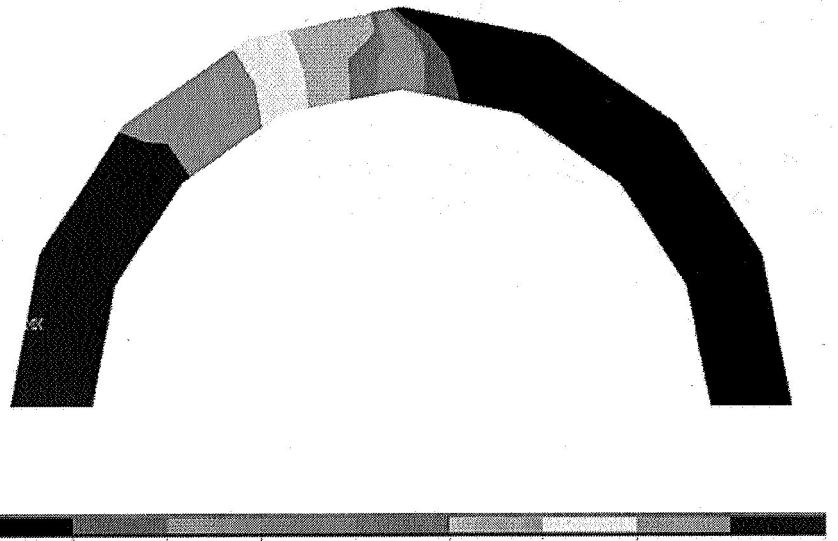
Figure 4: Example Structural FEA model.

Al 1200-H4, t=0.0160 m
Lunar Cement, t=0.0805 m
Lunar Cement, t=0.2523 m
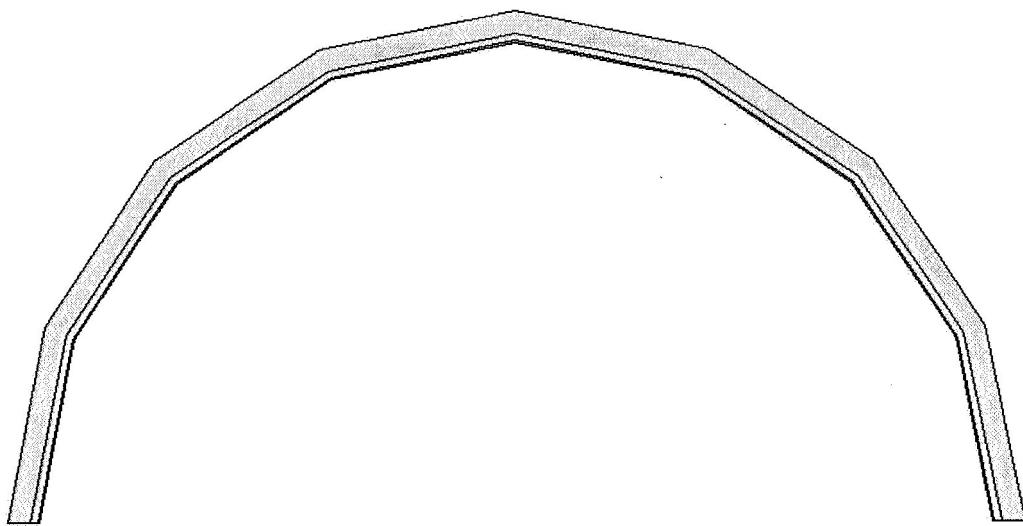
Figure 5: An example optimized habitat design.