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RELIABILITY of STRUCTURES for the MOON

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Abstract

The subject of risk and reliability for lunar structures is introduced and critical issues are introduced. Our purpose is to suggest an approach to the complicated lunar structure reliability question, the difficulty being that the estimation of reliability of unique structural types on a planetary body on which no construction has occurred has little precedence.

1 BACKGROUND

Concepts for lunar base structures have been proposed since long before the dawn of the space age. We will abstract suggestions generated during the past quarter century, as these are likely to form the pool from which eventual lunar base designs will evolve. Significant studies have been made since the days of the Apollo program, when it appeared likely that the Moon would become a second home to humans. For an early example of the gearing up of R&D efforts, see the Army Corps of Engineers study [1]. During the past decade these studies have intensified, both within NASA and outside the Government in industry and academe. The following references are representative: [2, 3, 4, 5, 6, 7, 8].

The emphasis below is on structures for human habitation, a technically challenging fraction of the total number of structures likely to comprise the lunar facility. The test for any proposed lunar base structure is how it meets certain basic as well as special requirements. On the lunar surface, numerous constraints must be satisfied by all designs. These are different than those for terrestrial or orbital structures, as will be discussed later. A number of structural types have been proposed for lunar base structures. These include concrete, metal frame, pneumatic, and hybrid structures. In addition, options exist for subsurface architectures and the use of natural features such as lava tubes. Each of these approaches can in principle satisfy the various and numerous constraints, but differently.

A post-Apollo evaluation of the need for a lunar base has been made [9] with the following reasons given for such a base: lunar science and astronomy, as a stimulus to space technology and as a test bed for the technologies required to place humans on Mars and beyond, the utilization of lunar resources, establishment of a U.S. presence, stimulate interest in young Americans in science and engineering, and as the beginning of a long-range program to ensure the survival of the species.

The potential for an astronomical observatory on the Moon is very great and it could be serviced periodically in a reasonable fashion from a lunar base. Several bold proposals for astronomy from the Moon have been made [10]. Nearly all of these proposals involve use of advanced materials and structural concepts to erect large long-life astronomy facilities on the Moon. These facilities will challenge structural designers, constructors, and logistics planners in the 21st Century [11, 12]. One example is a 16-meter

diameter reflector with its supporting structure and foundation currently being investigated by NASA and several consortia.

Selection of the proper site for a lunar astronomical facility, for example, involves many difficult decisions. Scientific advantages of a polar location for a lunar base [13] are based on the fact that half the sky is continuously visible for astronomy from each pole and that cryogenic instruments can readily be operated there due to the shaded regions in perpetual darkness. Disadvantages also arise from the fact that the sun will essentially trace the horizon, leaving the outside work space in extreme contrast, and will pose practical problems regarding solar power and communications with Earth, requiring relays.

2 INTRODUCTION

This paper examines risk and reliability issues surrounding the establishment of structures for human habitation on the Moon. Some of these discussions have been initiated elsewhere [14, 15, 16], and the reader is urged to look there for the technical details. Human safety and the minimization of risk to "acceptable" levels is always a top consideration for any engineering project. The Moon offers new challenges to the engineering designer. Minimization of risk implies in particular structural redundancy, and when all else fails, easy escape to safety for the inhabitants. The key word is "acceptable". It is a subjective deliberation, deeply rooted in economic considerations. *What is an acceptable level of safety and reliability for a lunar site, one which must be considered to be highly hazardous?* Such questions go beyond engineering considerations and must include policy considerations: *Can we afford to fail?*

Reliability is a specialized term for the analysis and design of systems where certain aspects of the environment and system have associated uncertainties. Thus, design requires explicit accounting of evolutionary processes which are inherently nondeterministic. This fact makes estimation of risk and reliability design complex activities.

The problem of designing a structure for construction on the lunar surface is a difficult one, discussed here only in relation to risk and reliability. Some important considerations necessary in a detailed reliability study include:

- the relationships between severe lunar temperature cycles and structural and material fatigue, a problem for exposed structures,
- structural sensitivity to temperature differentials between different sections of the same component,
- very low-temperature effects and the possibility of brittle fractures,
- outgassing for exposed steels and other effects of high vacuum on steel, alloys, and advanced materials,
- factors of safety, originally developed to account for uncertainties in the Earth design and construction process, undoubtedly need adjustment for the lunar environment, either up or down depending on one's perspective and tolerance for risk,
- dead loads/live loads under lunar gravity,
- buckling, stiffening, bracing requirements for lunar structures, which will be internally pressurized, and
- consideration of new failure modes such as those due to high-velocity micrometeorite impacts.

Many of these considerations are well understood in a basic sense, and need to be expanded upon for the lunar site. Some of these discussions have begun [17], in particular regarding the design process for an extraterrestrial structure. The quantitative specifics of the above list require massive efforts which are beyond the possibilities of those resulting in this paper.

2.1 Loading and environment

Any lunar structure will be designed for and built with the following prime considerations: (i) $\frac{1}{6}g$ gravity, (ii) internal air pressurization, (iii) shielding, (iv) vacuum, (v) dust, (vi) ease of construction, and (vii) use of local materials. More details on the environment are available elsewhere.

3 RISK and RELIABILITY

In this section, the key concerns of lunar structural reliability are expounded. In particular: What failure rate is acceptable? What factors of safety, and levels of redundancy, are necessary to assure this failure rate?

What failure rate is acceptable? Since it is generally accepted that one cannot economically design for zero risk, the next logical consideration is the level of acceptable risk. One way to begin to answer such a question is to study the sources of natural risks to a system in its intended environment. In particular, examine all natural phenomena and determine the risk exposure of the structure to each phenomenon. Some, such as meteorites of a certain size, can destroy a facility, but occur infrequently and therefore need not be designed against. Each of these risks define a time limit (in the probabilistic sense) to structural life; these may be independent or correlated. Thus, the probability of occurrence of a catastrophic meteorite hit is a small risk, perhaps the smallest encountered risk, and therefore may be viewed as the base risk against which other risks may be weighed. Other natural risks may be ascertained as best as possible, compared to the base risk, and then considered within the overall reliability analysis.

Next, man-made risks are to be assessed. Examples are the following: probability of explosion of liquid oxygen tanks, likelihood of projectiles piercing critical structural component due to accidents, thermal cycle fatigue, and human factors. These can be estimated and compared to the above base risk. All these "component" risk factors must be assessed, and, with engineering judgment (weighed somewhat by political considerations¹), acceptable risk decided upon.

For example, let $R_m = P\{\text{meteorite}\}$, the probability that a destructive meteorite will strike a site on the Moon during the period of a year. Further, let $R_f = P\{\text{thermal fatigue}\}$, be the probability that a certain number of thermal cycles in one year will result in material failure. Each such risk measure can be estimated independently, any correlation established, and then one may define a minimum necessary design risk as

$$R_{\min} = \text{Min}\{R_m, R_f, \dots\}. \quad (1)$$

This will be a measure of the smallest risk necessary for the structure. This actually may be too small to be economically acceptable, but it is a starting point. When one further considers that structures will be designed to be compartmentalized and modular, accessible and repairable, then it begins to appear possible to increase the value of the acceptable design risk R_{\min} to be used in the preliminary designs.

As much warning as possible is desired of an impending failure. Therefore, one cannot accept a *first-excursion failure*. Structural concepts must allow for progressive failure.

What factors of safety, and levels of redundancy, are necessary to assure this failure rate? Given an agreed upon acceptable level of risk, it becomes necessary as a practical matter to establish a design

¹Recall the cost to the space program due to the shuttle Challenger disaster.

philosophy. For example, what factor of safety do we build into the "lunar design code"? Since the lunar site provides designers with the most uncertainties of any engineering project, with few opportunities to obtain experience or data, one philosophy would demand higher than Earth factors of safety. However, one may decide to approach this question from another perspective. Consider the site to be inherently high-risk and, just as we accept high risks for test pilots, we should accept a high-risk approach to a lunar outpost design concept. Both approaches can be justified.

Redundancy is a separate question. Once a basis has been set for acceptable risk and safety factors, the designer must be ingenious in the conceptual design, optimizing the design so that overall risk is as close as possible to the acceptable level. In addition, risk should be distributed throughout the site in accordance with the criticality of the various parts to the overall mission.

This is a difficult problem, requiring the study of competing structural concepts.

How does logistics interplay with considerations of risk and reliability? The link is quite close. Generally, one has two options when a component or system fails: replace or repair. Inventories cannot be large enough to always be able to replace components. Thus, uncovered failures will be encountered. Such failures may have little impact on the safety of lunar inhabitants. However, high risk failures must be accounted for in any design.

Reliability and safety are linked to the maximum amount of payload that can be brought to the lunar facility in the minimum amount of time. This *minimum time to maximum payload* defines the absolute necessary self-sufficiency time for the lunar inhabitants. During this time, local replacement and/or repair are mandatory to recover from and survive significant failures. Logistic requirements, therefore, become important at an early stage of the design development cycle.

We see how redundancy in design becomes a crucial aspect of the design concept. Furthermore, the concept must incorporate ease of repair and reconditioning. At a more refined level, this implies that commonality of parts be a strategic concern and therefore a design constraint.

Consider the following design approach. A large-scale lunar outpost, if designed for some low risk scenario, would be a complex and expensive undertaking, primarily because humans are very delicate and the Moon so far away for rescue. If instead the lunar outpost is designed to higher risk tolerances, one which would ensure material safety but less so human safety, significant cost savings would be possible. To ensure high human safety, a second, smaller facility would be in place, most likely in a central and easily accessible site. This smaller facility would be designed to support the base population for a minimum amount of time, that is, the minimum time to maximum payload. The added cost of the smaller facility will be much less than the cost to bring the complete lunar base to those same high standards. Some thought is being given to the use of a long-term pressurized rover as part of this safety net.

Are smart structures of importance for a site such as the Moon? Invariably, yes if the "smart" components are more reliable than the structure of which they are a part. Assuming this to be the case, then, at the minimum, structures must be completely scoured and monitored in order to have warning of impending failures and problems. Some self-correcting capabilities are desirable, for example, for inflatable structures should any leakages occur.

4 KEY UNIQUE ISSUES of the LUNAR SITE

A brief review of lunar base structural concepts has been presented. The subject of risk and reliability for lunar structures is introduced and critical issues outlined and discussed. Key ideas presented are that

- before a particular design reliability is specified for a lunar structure, one must become aware of the design philosophy for the project: is it to be a high-risk endeavor?

- individual natural risks of the site must be estimated, thus providing a base from which overall possible reliability can be provided, and
- logistic considerations play an integral part in the design philosophy.

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