

Optimization of Crew Shielding Requirement in Reactor-Powered Lunar Surface Missions

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Abstract - On the surface of the moon -and not only during heightened solar activities- the radiation environment is such that crew protection will be required for missions lasting in excess of six months. This study focuses on estimating the optimized crew shielding requirement for lunar surface missions with a nuclear option. Simple, transport-simulation based dose-depth relations of the three (galactic, solar, and fission) radiation sources are employed in a 1-dimensional optimization scheme. The scheme is developed to estimate the total required mass of lunar-regolith separating reactor from crew. The scheme was applied to both solar maximum and minimum conditions. It is shown that savings of up to 30% in regolith mass can be realized. It is argued, however, that inherent variation and uncertainty -mainly in lunar regolith attenuation properties in addition to the radiation quality factor- can easily defeat this and similar optimization schemes.

I. INTRODUCTION

In addition to other flight risks and hazards, space flight beyond the confines of the Earth's magnetic field will have to face the challenges of space radiation exposure. In extended lunar surface missions protection of crew and systems require shielding strategies against various sources of space radiation fields, both natural and man-introduced. Due to various degrees of variability, unpredictability, as well as -in some critical areas- lack of basic data, guaranteeing safe levels of exposure poses a special challenge.

Exposure estimates for shielding solutions as well as for safety assessment must be formulated and optimized based on incomplete data, constrained by both technical and non-technical factors. One of the more consequential constraints, albeit somewhat subjective, is that of ALARA, "as low as reasonably achievable."

A main task of mission designers is to minimize requirements on structure and function while insuring maximum protection for crew and systems, consistent with ALARA. ALARA is currently NASA's accepted guideline as well as being a part of the legal requirements with regard to ionizing radiation exposure and crew health and protection.

Shielding solutions and dose and risk assessments to be consistent with ALARA must rely on robust and accurate exposure estimates. Objective comparisons among these solutions will clearly need reliable estimates as well.

To various degrees, such estimates are hampered by inherent uncertainties; in basic knowledge of the radiation environment itself, its transport and interaction in various media of complex geometry and composition, and most critically, in the human biological response to such exposure.

In the absence of more empirical data, on the one hand, and the increasing complexity of the modality and appli-

cations by which (and for which) one arrives at these estimates, on the other, such estimates are best viewed as guidelines rather than predictions.

Given the expected doses, this parametric study focuses on estimating the optimal crew shielding requirement in lunar surface missions with a nuclear option. Possible missions are assumed to take place during both low and high solar activity. Specificity due to the mission's location on the lunar surface is not taken into account. For this study's purposes, these missions are assumed to only include a crew habitation module and powered by a small fission reactor placed at some distance from this module. No other details about the reactor or the habitation module, e.g., their geometric configurations and specific structures or subsystem are either assumed or used.

Independent of the exact type or chemical composition of the shielding material, any shielding solution will require a certain amount of areal density to reduce the expected crew exposures to acceptable levels. For this study, lunar regolith, albeit in an idealized form, is assumed to be the shielding material of choice.¹

The estimates and method presented here are meant to help mission designers put in perspective the expected cumulative exposure -due to natural and introduced sources- vis-à-vis the amount of regolith mass required for crew protection. For example, for logistical considerations, one may want to minimize the separation distance between habitat and reactor while maintaining maximum protection. Conversely, one may want to minimize the amount of regolith to be used by maximizing the distance. Ideally, in both extremes as well as for all estimates in between, required regolith mass needs to be optimized for each separation distance.

Since shielding will be required and can be used for both reactor and crew, a self-consistent approach would be to estimate, at a given distance, the optimal and also

total amount of regolith mass separating crew from reactor. Because of the additive nature of the solution, this amount can be thought of as the sum of habitat shielding and reactor shielding. This self-consistent solution should allow for more flexibility in allocating material resource and/or construction effort between reactor and habitat.

A brief survey of the radiation environment and exposure doses is given, followed by a description of the dose-depth relations used and the 1-dimensional optimization scheme. Sample results for optimized required regolith mass and reactor-crew separation for missions during solar minimum and solar maximum conditions, superimposed on a 'typical' large solar particle event, are provided, followed by a discussion and conclusions.

II. THE RADIATION ENVIRONMENT

Energetic, high-charge galactic cosmic-ray ions (GCR) and solar energetic particles (SEP) constitute the main (natural) source of this intense radiation environment. The energy range of these particles spans more than eight orders of magnitude (from thermal to ultra-relativistic) while their atomic numbers populate the entire stable nuclides of the periodic table.

Atomic charges of 1 (hydrogen) through 26 (iron), however, are considered important for crew radiation safety and shielding purposes. By number, hydrogen constitutes about 90%, helium 7%, and all others 3% of the GCR ions. The intensity of the ambient GCR component ($\sim 1 \text{ cm}^{-2}$) peaks around 500 MeV/nucleon and is modulated by a factor of about three over the 11-year solar cycle.² During solar maximum and due to the actions of the solar wind, access to the heliosphere by diffusing GCR ions is reduced. As a result the GCR component appears depressed in the inner heliosphere.

During heightened solar activities, solar particle events, while random in occurrence, are more frequent and strong enough to transport SEPs (by a propagating shock driven by a coronal mass ejection or CME) to Earth's orbit and beyond. The SEP component is mostly composed of energetic protons, peaks around few tens of MeV in energy, but can vary widely in intensity ($\sim 10^7 \text{ cm}^{-2}$) as well as in the shape of its energy spectra. The so-called 'large' events, e.g., the October-1989 event, can be an order of magnitude more intense than the 'average' event, and many orders of magnitude above the quiescent conditions, lasting hours to 2-3 days.²

Relatively little is known (or can reliably be predicted) about the photospheric, coronal, and heliospheric mechanisms responsible for CMEs and large SEPs. Furthering our basic understanding in these areas remains a key prerequisite³ of the Exploration Vision.

In addition to these natural sources of space energetic particles, there likely to be man-introduced radioactive and fission sources for power and even propulsion purposes as well. A number of studies^{4,5} for the power re-

TABLE I: 1999 NCRP-recommended dose limits by organ and exposure duration.

Limit (cSv)	Bone Marrow	Eye	Skin
30-day Exposure	25	100	150
Annual	50	200	300
Career	50-300	400	600

quirements during future lunar surface missions, for example, suggest that the need is on the order of tens of kilo-watts of electric power.

For this level of power, chemical, solar, and radio-isotope sources may be insufficient or impractical. For crew protection purposes, fission reactors are considered mainly as sources of energetic neutrons and gamma rays (photons). Contributions of these sources to the total expected crew dose is due mostly to prompt neutrons.

Prompt neutrons are produced in the fission process of the fissile material, e.g., U-235, Pu-239. Most of these are energetic or 'fast' neutrons produced (at $\sim 10^{14} \text{ cm}^{-2}$) as direct fission products with an average energy of about 2 MeV.

Photons (at $\sim 10^{10} \text{ cm}^{-2}$) are produced both as direct products of the fission reaction as well as a result of the subsequent decay of the fission radioactive products. For shielding purposes, however, gamma rays with energy less than 0.6 MeV are typically ignored.⁶

III. EXPECTED EXPOSURE LEVELS

Crew exposure levels are typically expressed in dose-equivalent units. Dose-equivalent in units of Sievert (Sv) is calculated from the dose corrected by a dimensionless, multiplicative factor called the radiation 'quality factor', or Q-factor.⁷ Ionizing radiation like energetic heavy ions (e.g., GCR ions) are characterized by high Q values. Uncharged neutrons are also assigned high Q values to underscore their more serious health hazards relative to either x-rays or gamma rays at the same energy. Unlike the physically describable and measurable dose, the Q-factor is an empirical, dimensionless variable assumed to 'represent' the majority of the biological effects associated with exposure to ionizing radiation - but without specifying such effects by their end points or response functions.⁸

Estimating the health risk -and thus shielding requirement- associated with space radiation exposure is hampered mostly by uncertainties in the biological response.⁹ Other factors associated with the radiation environment, its physical interactions, as well as with dose and dose-rate volatilities, also contribute. As will be touched upon later on, large ($\sim 200\%$) uncertainties in the Q-factor can significantly affect shielding requirements, and hence any optimized estimates of which as well.

TABLE II: Expected doses on the lunar surface with and without shielding (no nuclear power source assumed).

Duration (days)	GCR (cSv)	SEP (cSv)	Mission (cSv)
10	0.3/0.8	7.5/20.5	7.8/21.3
30	1.0/2.5	7.5/20.5	8.5/23.0
180	6.0/15.0	7.5/20.5	13.5/35.5
360	12.0/30.0	7.5/20.5	19.5/50.5

The National Commission on Radiation Protection (NCRP) publishes and regularly updates recommended limits appropriate for low-Earth orbits (LEO) missions. Table I lists the 1999 recommendations¹⁰ for dose limits for organs for all ages for 30-day, annual, and career exposures. [Note the 50-cSv limit for bone marrow.]

To put this 50-cSv limit and the other NCRP limits in perspective, on the International Space Station (ISS), for example, during solar maximum, the average effective dose was measured to be about 6.1 cSv while the effective dose-rate was about 0.037 cSv/day.¹¹ Note though that on the ISS, in addition to protective geomagnetic effects (which are not present outside the magnetosphere), shielding equivalent to about 5-10 cm of aluminum is provided by the ISS structure and systems' materials.¹²

On the lunar surface, the dose due to the (isotropic) GCR source is reduced by a half due to the shadow shielding effect of the Moon itself. The introduction of a small nuclear fission reactor (~ 25 -kWe) is estimated¹³ to add about 5 cSv/year at a 'safe distance' from its shielded core. Both water and regolith have been considered for core shielding.¹³

Table II contrasts typical expected^{14,15} doses on the surface of the Moon with and without a 50-cm thick shield made of idealized lunar-regolith, equivalent to 11 inches of standard aluminum, assuming solar-minimum GCR conditions and superimposed on an Aug.-1972 class SPE. Given currently accepted limits for LEO missions (cf. Table I) these expected exposure figures clearly suggest that extended (> 6 months) surface missions will require shielding solutions, even without the presence of a nuclear fission source.

IV. PARAMETERIZING THE DOSE-DEPTH RELATIONS

For the purpose of this parametric study, dose as a function of depth in lunar regolith from all three radiation sources, i.e., GCR, SEP, and fission sources (we ignore contribution from neutron albedo) will be assumed to have simple closed form expressions amenable to variational analysis. To that end, the GCR dose-depth relation is taken to be

$$D_1(x) = A_1 \exp(-\lambda_1 x) + B_1, \quad (1)$$

where $D_1(x)$ is the dose-rate in cSv/yr, x is total regolith separation mass -between reactor and crew- in g/cm^2 (i.e., an arbitrary combination of reactor depth and habitat shielding) and λ_1 is the regolith attenuation coefficient for GCR in $(\text{g}/\text{cm}^2)^{-1}$.

The constants $A_1 = 74$ cSv/yr and $B_1 = 28$ cSv/yr as well as $\lambda_1 = 0.06$ $(\text{g}/\text{cm}^2)^{-1}$ are estimated using fits to 3-dimensional Monte-Carlo simulations assuming solar minimum conditions.¹⁶ For solar maximum conditions, the values are: $A_1 = 54$, $B_1 = -24$, and $\lambda_1 = 0.02$.

For this approximation as well as for the other two below, lunar regolith is idealized as being composed of 74% oxygen, 11% silicon, 7% aluminum, 4% calcium, and 4% magnesium by weight. The density of this aggregate is taken to be $1.5 \text{ g}/\text{cm}^3$.

The GCR/SEP particle flux is transported through a thick slab of this idealized regolith, suffering both energy as well as charge losses. The transported flux is converted into dose and dose-equivalent quantities using the ICRP-1991 conversion convention.¹⁷

The SEP transported flux is similarly assumed to be of a simple (analytic) form,

$$D_2(x) = \frac{A_2}{B_2 + \lambda_2 x}, \quad (2)$$

where $D_2(x)$ is now the event-integrated dose in cSv, $A_2 = 400$ cSv, $B_2 = 1$ cSv, and $\lambda_2 = 1.08$ $(\text{g}/\text{cm}^2)^{-1}$. These numbers are based on 3-d transport simulations through a finite slab of lunar regolith as described above and for an assumed August-1972 class SPE.

The dose-depth approximation as a function of radial distance from the reactor's location is also based on 3-d transport simulations.¹³ The conceptualized reactor in the simulation is a moderated spectrum, NaK cooled, Hastalloy/UZrH reactor with open-lattice pin geometry.¹⁸ The reactor provides thermal power to a 25-kWe Stirling engine power conversion system. The cylinder-shaped system (reactor, water-shield, and power-conversion system) stands about 2 m high and is about 1 m in diameter.

The reactor's transported¹³ neutron and gamma fluxes are assumed to originate from a shielded core. To first order, the reactor's dose-depth relation for a given r (surface separation distance in m) can be approximated as

$$D_3(x) = (A_3 \exp(-\lambda_3 x) + B_3)/r^2, \quad (3)$$

where $D_3(x)$ is the dose-rate in cSv/yr, $A_3 = 2 \times 10^6$ cSv/yr-m², $B_3 = 3 \times 10^3$ cSv/yr-m², and $\lambda_3 = 1.87 \times 10^{-2}$ $(\text{g}/\text{cm}^2)^{-1}$.

V. OPTIMIZATION SCHEME

To formulate a 1-dimensional variational scheme, we re-express Eq. (3) as a controllable, 'dynamical' system as:

$$\frac{\partial D_3}{\partial x'} = -D_3(x') + \frac{B_3}{r^2} c(x'), \quad (4)$$

where $x' = \lambda_3 x$ is the ‘dynamical’ variable, $c(x')$ is the control variable, and r is a parameter. The controllability of the process is assumed¹⁹ based on the system being autonomous, linear in x' , and possessing of a stable, (uncontrolled) ‘equilibrium’ state as $x' \rightarrow \infty$.

The initial condition, $D_3(0)$, is taken to be the uncontrolled state at $x' = x = 0$ where the control variable c is identically equal to unity. Formulated this way, the objective becomes to find the optimal regolith mass, $x' = x^*$, such that for a given r the functional:

$$J[x^*(r)] = \int_0^{x^*(r)} \left[\tau + \frac{1}{2} c^2(x') \right] dx', \quad (5)$$

is minimal while assuring a safe dose, i.e., $D_3(x^*) \leq D_s$.

An optimal solution is assumed to exist due to the convexity property of $J[x^*(r)]$, i.e., over its entire domain \mathcal{D} , $J(x')$ assumes a minimum value at each and every stationary point in \mathcal{D} . This property of J assures²⁰ that

$$J(x') \geq J(x^*) + \nabla J(x^*) \cdot (x' - x^*); \forall x', x^* \in \mathcal{D}, \quad (6)$$

where ∇J is the gradient of J .

The safe dose D_s is taken to be the dose limit (e.g., an NCRP limit) including the contributions due to GCR and SEP exposure as a function of depth x' . The first term in this ‘cost’ functional J is taken to be solely determined by the total mass required, x^* , while the second term by the incremental amount of mass needed to reduce the incurred dose to its current level at this $x'(r)$ point.

The constant τ is a measure of this distribution between the two: When $\tau \gg 1$, this corresponds to a solution for achieving a safe dose level at a given r with as little regulation, i.e., r -manipulation, as possible. Conversely, when $\tau \ll 1$, the safe dose level is achieved for maximal manipulation (regulation). Note that no optimal solution exists when τ is identically zero.

We proceed by assigning a ‘Hamiltonian’ to the process according to the Pontryagin maximal principle.^{19,21} The Hamiltonian remains constant along an optimal trajectory, $x' = 0 \rightarrow$ to $x' = x^*$. The general form for a 1-dimensional Hamiltonian is:

$$\mathcal{H} = \nu_0 \dot{\mu}_0 + \nu_1 \dot{\mu}_1. \quad (7)$$

The μ variables are called state variables while the ν ones are called the co-state variables (analogous to generalized coordinates and generalized momenta in analytical dynamics). Both sets are given by Hamilton’s equations of motion,

$$\dot{\nu}_0 = -\frac{\partial \mathcal{H}}{\partial \mu_0}, \quad \dot{\nu}_1 = -\frac{\partial \mathcal{H}}{\partial \mu_1}, \quad (8)$$

$$\dot{\mu}_0 = +\frac{\partial \mathcal{H}}{\partial \nu_0}, \quad \dot{\mu}_1 = +\frac{\partial \mathcal{H}}{\partial \nu_1}. \quad (9)$$

At each point along the optimal trajectory the Hamiltonian remains minimized. For our system,²¹

$$\mathcal{H}(x') = -\left[\tau + \frac{1}{2} c^2(x') \right] + \nu_1 [-D_3(x') + c(x')]. \quad (10)$$

Solving for ν_1 and c and applying initial and safety conditions on D_3 gives the following transcendental relation for $x^*(r)$:

$$D_3(0)/D_r \exp x^* - D_s(x^*)/D_r - 2\beta \sinh x^* = 0, \quad (11)$$

where $D_r = B_3/r^2$ and β is a constant of the ‘motion’. Constants of the motion α and β are determined from the initial and safety conditions,

$$\beta = D_3(0) - \alpha/2, \quad (12)$$

and where α is the negative root of:

$$\alpha^2 - 2\alpha D_3(0) - 2\tau = 0. \quad (13)$$

Next, we need to estimate the value of the constant τ for this particular optimization, Eq. (4), and the choice for the functional form of J , Eq. (5).

The directional derivative of J at c is defined as²⁰:

$$\delta J(c; d) \equiv \lim_{\varepsilon \rightarrow 0} \left[\frac{J(c + \varepsilon d) - J(c)}{\varepsilon} \right] \quad (14)$$

$$= \left. \frac{\partial J}{\partial \varepsilon} (c + \varepsilon d) \right|_{\varepsilon=0}. \quad (15)$$

From Eq. (5),

$$J(c + \varepsilon d) = \int_0^{x^*(r)} \left[\tau + \frac{1}{2} c^2 + \varepsilon c d + \frac{\varepsilon^2}{2} d^2 \right] dx'. \quad (16)$$

Upon subtracting $J(c)$, dividing by ε , and taking the limit as $\varepsilon \rightarrow 0$, we get

$$\delta J(c; d) = \int_0^{x^*(r)} c(x') d(x') dx'. \quad (17)$$

Now, from the convexity property of J ,

$$\delta J(c; d) = \frac{\partial J}{\partial c} d, \quad (18)$$

and the symmetry of Eq. (17) with respect to $c \leftrightarrow d$ and recalling that $c = 1$ corresponds to the uncontrolled, initial condition, we have

$$\delta J(c; 1) = \delta J(1; c) = \frac{\partial J}{\partial x'} \left(\frac{\partial c}{\partial x'} \right)^{-1}. \quad (19)$$

We know from the general solution of Eqs. (4-11) that $c(x') \propto \exp(x')$. It follows then from the above relation that to within a constant of order unity, the numerical value of τ should be $\sim B_3$.

It should be noted that for this particular optimization scheme of Eq. (3), a different approach would have been to use the conditions on the Hamiltonian, i.e., minimal (including zero) and unchanged along an optimal trajectory, rather than minimizing the cost functional J as we did here. The alternate approach should, in principle, give the same results, but no attempt, for self-consistency, has been made here to demonstrate as much.

The first-order, linear optimization scheme presented here should also be treated as parametrization specific insofar as the form of Eq. (3) is concerned, i.e., its x' and r -dependence and our treatment, for purposes of estimating the optimal path $x' \rightarrow x^*$, of the variable x' as the 'dynamical' variable and r as being part of the control variable $c(x')$. No attempt has been made here to check for the applicability of the solution (controllability, existence, uniqueness, etc.) over wide ranges of the fit parameters, A_i , B_i , and λ_i . However, the theory of linear, first-order control problems, e.g., one described by Eq. (4), is well anchored and properties of the general solutions are known for sufficiently large phase and parameter spaces, especially so for autonomous, one-dimensional systems.

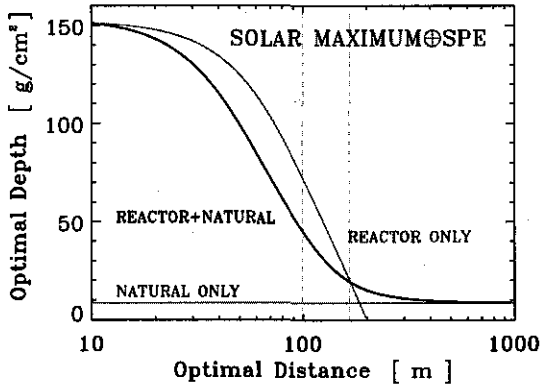


FIG. 1: Optimized reactor depth-distance solution for GCR solar maximum conditions superimposed on an August-1972 class SPE, for a 50-cSv/yr dose limit (see Table I). [Note that 'depth' in this calculation and on both figures refers to the total regolith mass, in g/cm², separating reactor from crew.]

The choice of the cost functional, Eq. (5), also affects the solution; convexity-wise we only used the simplest form of the functional, i.e., quadratic. Clearly, and as we discuss below, other forms need to be explored as well.

Finally, generalization of linear-state control problems to two and three dimensions is, in principle, straightforward. However, issues related to uniqueness and stability of the controlled solution become more critical in higher dimensions. Generalization of this particular optimization scheme to higher dimensions must be preceded by further numerical and analytical demonstrations of its wider applicability and utility.

VI. SAMPLE CALCULATION AND DISCUSSION

We apply the above optimization scheme to two mission scenarios; one during GCR solar-maximum conditions superimposed on an August-1972 class SPE (Figs. 1), and similarly for GCR solar-minimum conditions

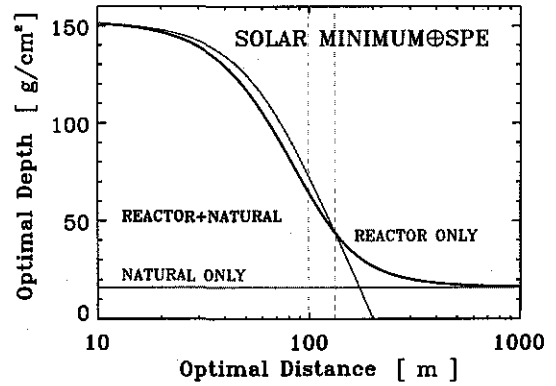


FIG. 2: Optimized reactor depth-distance solution for GCR solar minimum conditions superimposed on an August-1972 class SPE, for a 50-cSv/yr dose limit (see Table I).

(Fig. 2). In both cases, the shielding material is the idealized lunar regolith as described in Sect. IV, along with the parameterized forms and values of the transported radiation sources for each scenario. For each scenario, Eqs. (4-11) are solved using the fit (A_i , B_i , and λ_i) and optimization (α_i , β_i , and τ_i) parameters, self-consistently. These latter ones depend sensitively on initial conditions and hence they change from one scenario to the other. The dose limit, for reference, is taken to be the 50-cSv/yr level, i.e., the LEO 1999-NCRP annual limit for bone-marrow exposure (Table I).

For each scenario, as a function of distance from the reactor, shown on the figures is the optimized total (due to reactor plus natural) mass of lunar regolith required to keep the dose-rate level \leq the safe rate of 50 cSv/yr. Also shown is the required mass for reactor-only case, i.e., no GCR or SEP fields assumed, and for the natural-environment-only case, i.e., no reactor. After subtracting the mass requirement to shield against the GCR and SEP fields, the balance can, as mentioned earlier, be treated as an arbitrary combination of both the amount of shielding required for the reactor plus that for added shielding - due to the introduction of the reactor- for the habitat.

For example, for a surface mission during solar minimum, at a distance of 100 m from the reactor, from Fig. 2, the optimized total regolith shielding requirement is about 62 g/cm². Shielding against GCR and SEP fields requires about 16 g/cm². Note that the un-optimized reactor requirement (which is also the total here because it is larger than the natural overburden) is about 76 g/cm², i.e., a 23% saving in required mass due only to optimization. [For solar maximum conditions, Fig. 1, the saving is, of course, even larger (30-35%) because the natural environment overburden is lower.]

In addition, the 46-g/cm² requirement can be divided in a number of ways depending on other factors, e.g., availability and processing of regolith and reactor site preparation, between the actual required depth of the reactor system beneath the lunar surface and the actual

thickness of the added habitat protection against the reactor's radiation fields. This added flexibility is a result of treating the reactor and habitat shielding requirements self-consistently in this simple optimization scheme.

However, this self-consistent treatment is also reflected in the optimization cost. On Fig. 1, for example, and for distances larger than about 133 m from the reactor, the 'optimized' mass is larger than what is actually required. The reason being the 'cost' of optimizing the mass for any distance is always nonzero, as can be seen from Eq. (5). In this particular optimization scheme, the optimization becomes 'cost-ineffective' for large distances, but not large enough, i.e., for distances at which the reactor's fields become negligible compared to the natural overburden (~ 220 m for this study). Clearly, a more robust form for the cost functional, Eq. (5), is required to reduce the cost over a wider range of separation distance.

Also, the above assessment was based on an idealized regolith and its simulated attenuation properties against both natural and fission radiation sources. If one allows for an error margin of the same order in the attenuation properties of regolith (and not in its other physical properties²²), this saving all but disappears. Imprecision in basic regolith attenuation properties that is on the order of 50-75% will render any optimization scheme frivolous.

It is important to note that variations in regolith density alone, which has a range of 1.5-2.8 g/cm³, can easily contribute this level of imprecision. When coupled with uncertainties in modeling the radiation quality factor, it becomes clear that this and similar optimizations schemes are easily defeated by such large variabilities.

Unfortunately, some of these variabilities are inherent to shielding and radiation protection studies associated with crewed lunar surface missions, with or without a nuclear option.

VII. CONCLUSIONS

A parametric study was conducted to afford mission designers first-order estimates for the amount of lunar regolith required to protect the crew on a lunar surface mission from exposure to GCR, SEP, and neutron fields associated with a small fission reactor.

Since shielding is expected to be required for both reactor and crew, we have taken a self-consistent approach to estimate, at a given distance, the optimal (total) amount of regolith separating crew from reactor. The additive nature of the solution in this treatment should allow for some flexibility in allocating material resource and/or construction effort between reactor and habitat.

We use simple but simulation-based dose-depth relations for all three radiation sources in a 1-d optimization scheme. The objective is to estimate the optimal regolith mass between crew and reactor, as a function of their separation distance. The optimization scheme was based on

Pontryagin maximal principle.

The scheme was applied to both solar maximum and minimum conditions. Depending on mission's time profile, a saving of up to 30% in mass can be seen between optimized and un-optimized required regolith-mass estimates. However, it is argued that variation and uncertainty mainly in lunar regolith attenuation properties and in the radiation quality factor can easily defeat this and any other similar optimization scheme.

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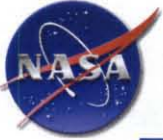
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Optimization of Crew Shielding Requirement in Reactor-Powered Lunar Surface Missions

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Boston, Mass., June 24-28, 2007*

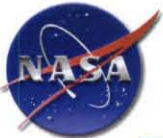
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Lunar Regolith and Shielding Requirements



- To protect crew and radiation-sensitive systems shielding will be required for extended (> 6 months) missions against:
 - the **natural galactic and solar particles'** fields
 - neutron and gamma-ray emissions associated with a nuclear (**fission**) power system
 - the **secondary components** of these sources
- Most shielding estimates of crew habitat require the shielding materials to have a **thickness of the order of a meter**
- A cylindrical habitat 10 m long with 4.5/5.5 m radii (i.e., 50-cm thick of regolith-like shield) will require about **150 metric tons** of shield material
- Similar requirement renders transported shielding materials mass prohibitive, suggesting
abundant lunar soil becomes a prime candidate for shielding purposes!



Expected Exposure Levels vs. Safe Limits



TABLE I: 1999 NCRP-recommended dose limits by organ and exposure duration.

Limit (cSv)	Bone Marrow	Eye	Skin
30-day Exposure	25	100	150
Annual	50	200	300
Career	50-300	400	600

TABLE II: Expected doses on the lunar surface with and without shielding (no nuclear power source assumed).

Duration (days)	GCR (cSv)	SEP (cSv)	Mission (cSv)
10	0.3/0.8	7.5/20.5	7.8/21.3
30	1.0/2.5	7.5/20.5	8.5/23.0
180	6.0/15.0	7.5/20.5	13.5/35.5
360	12.0/30.0	7.5/20.5	19.5/50.5



Statement of the Problem

Lunar regolith (in whatever variety) is likely to be used for shielding purposes for both habitat and reactor:

How does exposure to *both* natural and reactor's fields affect the estimation and optimization of required regolith mass/volume for shielding purposes?

How do these estimates, in turn, depend on other non-shielding assumptions, e.g., power requirements, logistics, regolith properties, etc.?

This study's result is essentially:

Even though saving of up to 30% or more –depending on mission's time profile– can be realized with optimization, variation and uncertainty, mainly in the lunar regolith attenuation properties and the radiation quality factor, can easily defeat this and similar optimization schemes!



Problem Abstracted



I. Radiation Sources

Idealized regolith: 74% O, 11% Si, 7% Al, 4% Ca, 4% Mn; 1.5 g/cm³

1. **GCR**: $\sim 1 \text{ cm}^{-2}$; protons – iron ions; peaks at $\sim 500 \text{ MeV/nuc.}$; solar-modulated

$$D_1(x) = A_1 \exp(-\lambda_1 x) + B_1$$

2. **SEP**: $\sim 10^7 \text{ cm}^{-2}$; protons; August 1972-class SPE

$$D_2(x) = \frac{A_2}{B_2 + \lambda_2 x}$$

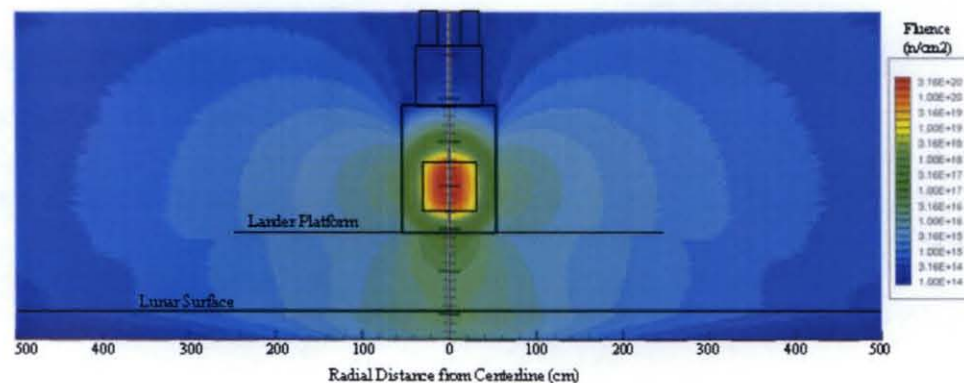


Problem Abstracted



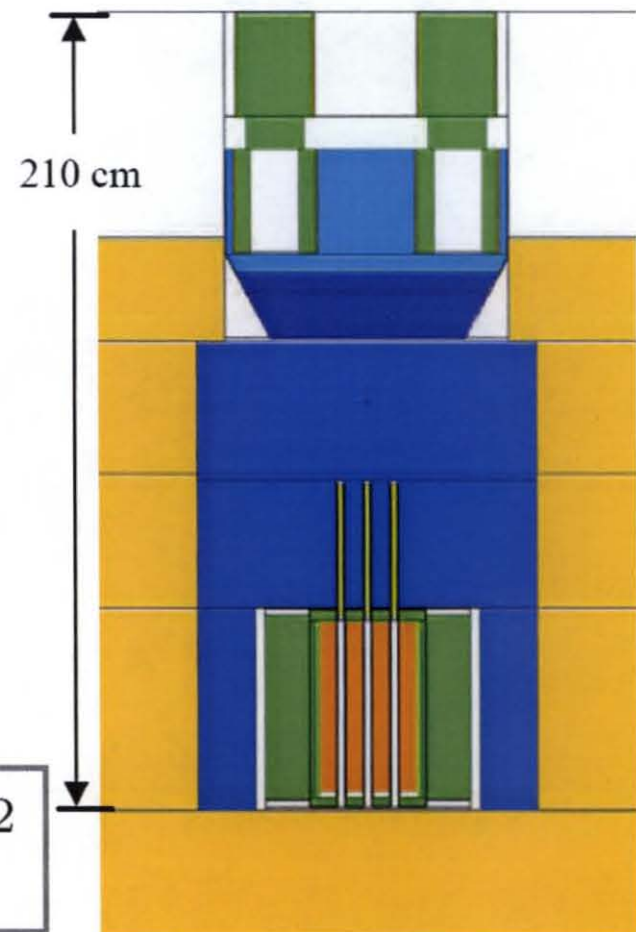
I. Radiation Sources

3. *Reactor*: 'snapf3' concept [Dixon et al. (2006)]



[Poston et al. (2006)]

$$D_3(x) = \left(A_3 \exp(-\lambda_3 x) + B_3 \right) / r^2$$





Problem Abstracted



II. Variational Scheme

Given: $\frac{\partial D_3}{\partial x'} = -D_3(x') + \frac{B_3}{r^2} c(x')$

for 'dynamic' variable x' and control variable $c(x')$, find the optimal path $x' = 0 \rightarrow$ to $x' = x^*$ that minimizes

$$J[x^*(r)] = \int_0^{x^*(r)} \left[\tau + \frac{1}{2} c^2(x') \right] dx'$$

with the convex property:

$$J(x') \geq J(x^*) + \nabla J(x^*) \cdot (x' - x^*); \forall x', x^* \in \mathcal{D}$$



Problem Abstracted



III. *Method* (Pontryagin maximal principle)

'Hamiltonian' remains minimal over optimal path:

$$\mathcal{H} = \nu_0 \dot{\mu}_0 + \nu_1 \dot{\mu}_1$$

$$\dot{\nu}_0 = -\frac{\partial \mathcal{H}}{\partial \mu_0} \quad \dot{\nu}_1 = -\frac{\partial \mathcal{H}}{\partial \mu_1}$$

$$\dot{\mu}_0 = +\frac{\partial \mathcal{H}}{\partial \nu_0} \quad \dot{\mu}_1 = +\frac{\partial \mathcal{H}}{\partial \nu_1}$$

$$\mathcal{H}(x') = -\left[\tau + \frac{1}{2}c^2(x')\right] + \nu_1[-D_3(x') + c(x')]$$



Problem Abstracted



IV. Result

The optimal mass $x^*(r)$ satisfies:

$$D_3(0)/D_r \exp x^* - D_s(x^*)/D_r - 2\beta \sinh x^* = 0$$

where β and other scales are determined from the ‘constants of motion’ and from the convexity property of the cost functional $J[x^*(r)]$

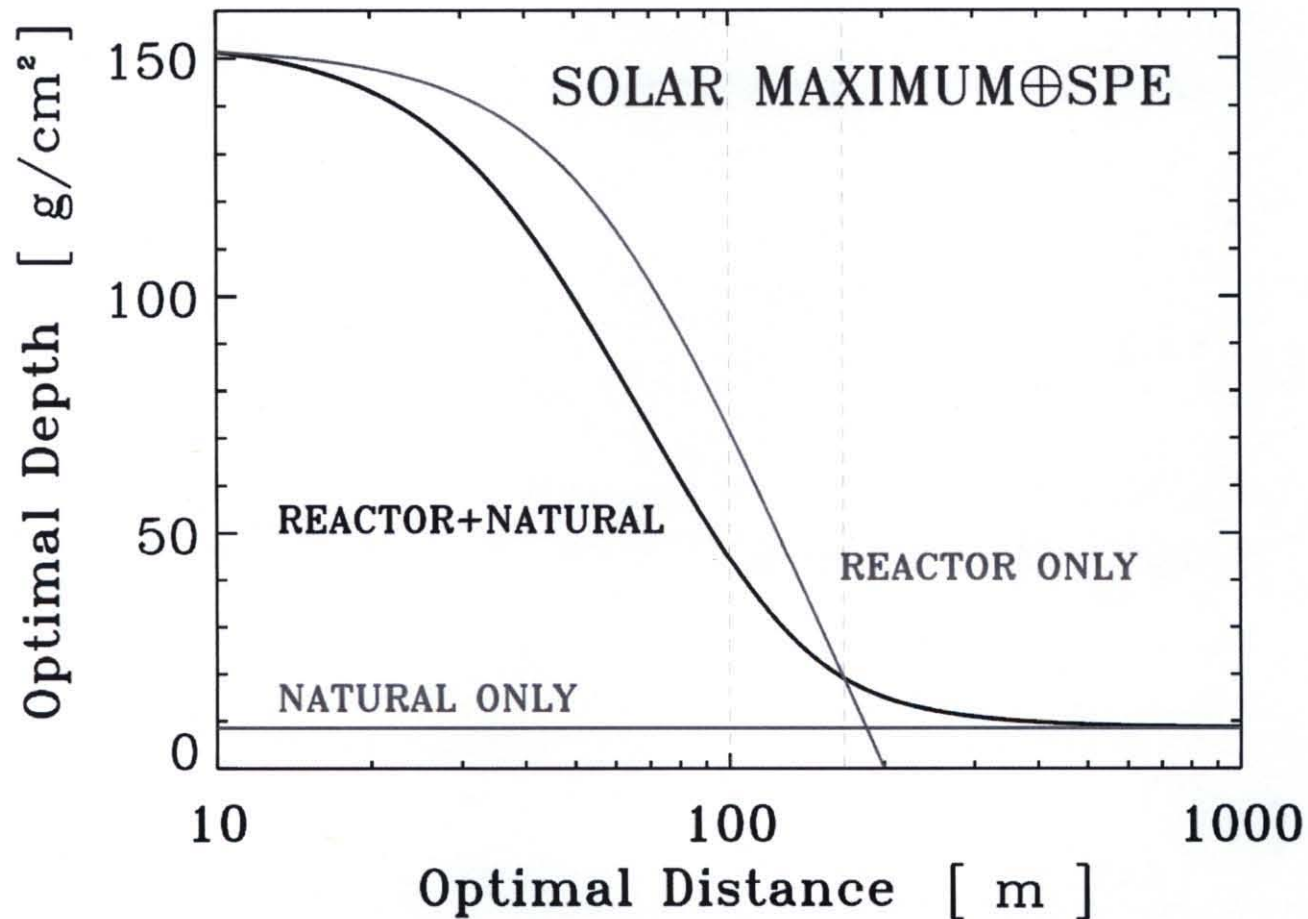
V. Caveat

Result is valid only for the assumed forms of $D_3(x')$ and $J[x^*(r)]$

Result is, however, valid for any final (safe) and initial conditions



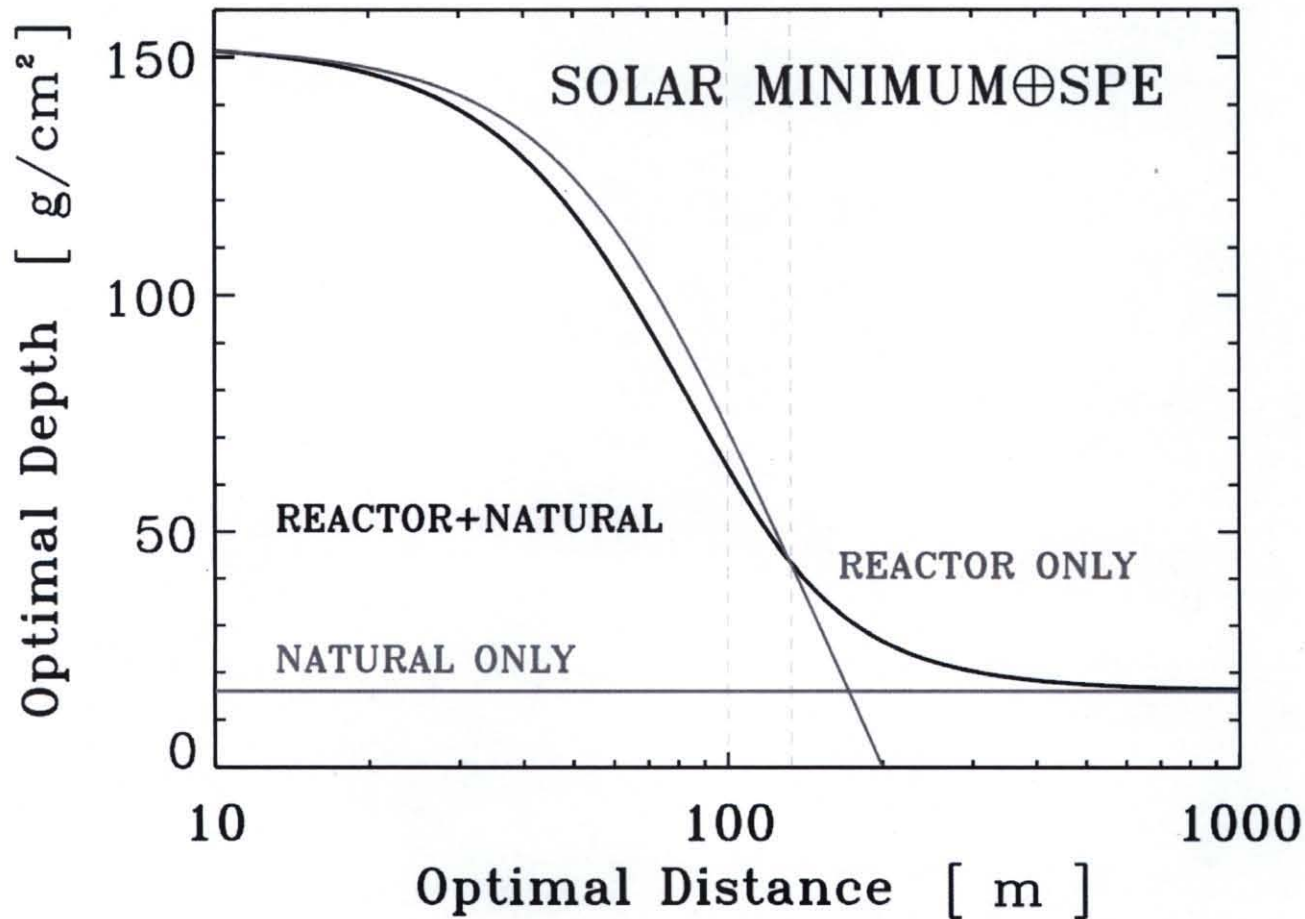
Sample Calculations



Optimized regolith mass vs. separation distance for a 50-cSv/yr dose-limit for a mission during **solar-maximum** GCR conditions superimposed on an Aug.1972-class SPE



Sample Calculations



Optimized regolith mass vs. separation distance for a 50-cSv/yr dose-limit for a mission during **solar-minimum** GCR conditions superimposed on an Aug.1972-class SPE



Remarks



While simple optimization scheme was specific to one particular dose relation, scheme is easily adaptable to others as well as being generalizable.

Other uncertainties notwithstanding, presented scheme has shown that lunar regolith to continue to be the 'material of choice' it needs to be better characterized against all three radiation sources, but specially reactor's neutrons.