

# An Astronaut's Risk of Experiencing a Critical Impact from Lunar Ejecta during Lunar EVA

Michael D. Bjorkman<sup>(1)</sup> and Eric L. Christiansen<sup>(2)</sup>

<sup>(1)</sup>Jacobs Technology, 2101 NASA Parkway, Houston TX, USA

<sup>(2)</sup>NASA Johnson Space Center, 2101 NASA Parkway, Houston TX, USA

## ABSTRACT

The Moon is under constant bombardment by meteoroids. When the meteoroid is large, the impact craters the surface, launching crater ejecta far from the impact potentially threatening astronauts on the lunar surface. In the early 1960's, the ejecta impact flux was thought no more than the sporadic meteoroid flux but with speeds one to two orders of magnitude smaller. However, the Lunar Module designers realized by 1965 that meteoroid bumpers do not perform well at the smaller ejecta impact speeds. Their estimates of the Lunar Module risk of penetration by ejecta were 25 to 50% of the total risk. This was in spite of the exposure time to ejecta being only a third of that to sporadic meteoroids.

The standard committee based the 1969 NASA SP-8013 lunar ejecta environment on Zook's 1967 flux analysis and Gault, Shoemaker and Moore's 1963 test data for impacts into solid basalt targets. However, Zook noted in his 1967 analysis, that if the lunar surface was composed of soil, that the ejected soil particles would be smaller than ejected basalt fragments and that the ejection speeds would be smaller. Both effects contribute to reducing the risk of a critical failure due to lunar ejecta.

The authors revised Zook's analysis to incorporate soil particle size distributions developed from analysis of Apollo lunar soil samples and ejected mass as a function of ejecta speed developed from coupling parameter analyses of soil impact-test data. The authors estimated EVA risk by assuming failure occurs at a critical impact energy. At these impact speeds, this might be true for suit hard and soft goods. However, these speeds are small enough that there may be significant strength effects that require new test data to modify the hypervelocity critical energy failure criterion. With these caveats, Christiansen, Cour-Palais and Freisen list the critical energy of the ISS EMU hard upper torso as 44 J and the helmet and visor as 71 J at hypervelocity. The authors then assumed that the lunar EVA suit fails at 50 J critical energy. This results in a 1,700,000 years mean time to failure using the results of this analysis and a 3,800 years mean time to failure using NASA SP-8013.

## 1 NOMENCLATURE

$B$	=	ejecta speed exponent in the cumulative ejecta mass scaling relation.
$F^+$	=	cumulative flux of ejecta fragments at the lunar surface with masses of $m_e$ or larger and ejecta speeds of $v$ or larger.
$k$	=	number density function of ejecta fragment sizes.
$K$	=	coefficient of the cumulative ejecta mass scaling relation.
$k_3$	=	largest ejecta particle mass as a fraction of the excavated crater mass.
$M$	=	cumulative distribution of ejecta mass with ejecta speeds $v$ or larger from the impact of a single meteoroid.
$M_0$	=	
$\mathcal{M}$	=	ejecta mass per unit area that lands with speed $v$ or larger from the impact of a single meteoroid at a distance $r$ or larger.
$\mathcal{M}^+$	=	ejecta mass per unit area per unit time that originates from the sporadic meteoroid flux that impacts at distance $r$ or larger.
$m$	=	incident sporadic meteoroid mass.
$m_0$	=	smallest sporadic meteoroid mass that will launch ejecta with speed $v$ or larger.
$m_e$	=	ejecta particle mass.
$m_e^*$	=	largest ejecta particle mass.
$n$	=	sporadic meteoroid flux probability density function as a function of sporadic meteoroid mass $m$ .

$r$	=	range between cratering event producing ejecta and the astronaut.
$R$	=	ratio of the number of penetrations by ejecta to the number of penetrations by sporadic meteoroids.
$U$	=	incident meteoroid speed.
$\langle U \rangle$	=	average incident meteoroid speed.
$v$	=	ejecta speed.
$V$	=	excavated crater volume.
$\vartheta$	=	angle ejecta makes with respect to the lunar surface upon leaving the crater bowl.
$\rho$	=	lunar soil mass density.
$\psi$	=	angle between the meteoroid trajectory and the normal to the lunar surface.

## 2 INTRODUCTION

Ejecta from cratering events produced by sporadic meteoroid impacts of the lunar surface may impact astronauts when in the vicinity of the cratering event. Gault and Shoemaker [1] were the first to consider the risk from ejecta impact and they concluded that the Moon had an atmosphere of lunar ejecta that extended from the surface to some 30 km altitude and that the flux of ejecta particles exceeds the interplanetary flux by a factor of 1,800 to 60,000. However, they thought that the lunar ejecta flux “should not greatly increase the hazard from catastrophic punctures, because the bulk of the ejected material travels at low speeds, but the abrasive action of the multiple impacts, even at low speeds, may present operational and maintenance problems for optical and solar-cell surfaces”.

Orrok [2] went on to consider the effect of ejecta speed on the threat of puncture and concluded in a study performed for the Apollo program office at NASA Headquarters that crater ejecta could no more than double the threat of puncture by meteoroids. He argued that the meteoroid transferred no more than its kinetic energy to the lunar ejecta. Because the spacecraft skin thickness that will stop an ejecta particle is proportional to the kinetic energy of the ejecta particle Orrok thought that the penetration rate at the surface of the Moon would at most be double the penetration rate in lunar orbit.<sup>1</sup> This result was widely circulated at the time as evidenced by the following quote from a NASA history of Apollo.

NASA issued a technical note reporting that scientists at Ames Research Center (ARC) Hypervelocity Ballistic Range, Moffett Field, Calif., were conducting experiments simulating the impact of micrometeoroids on the lunar surface. The experimenters examined the threat of surface debris, called secondary ejecta, that would be thrown from resultant craters. Data indicated that secondary particles capable of penetrating an astronaut's space suit nearly equaled the number of primary micrometeoroids. Thus the danger of micrometeoroid impact to astronauts on the moon may be almost double what was previously thought. [3]

It was also reported about the same time in Aviation Week [4] that while ejecta impacts could double the risk of a critical impact of an astronaut during EVA they could only make a minor 0.1% to 1% contribution to a bumper shielded spacecraft impact risk. However, engineers realized by 1965 that meteoroid bumpers do not perform well at the smaller ejecta impact speeds. Estimates [5] of the Apollo Lunar Module risk of penetration by ejecta were 25 to 50% of the total risk in spite of the exposure time to ejecta being only a third of that to sporadic meteoroids.

In 1967, Zook [6] showed how to extend Gault and Shoemaker's basalt cratering ejecta environment by considering a distribution of ejecta speeds, binned into three ranges of speed: 0 to 100 m/s, 100 to 250 m/s and 250 m/s to 1 km/s. The flux curves for each of the 3 speed bins are plotted in Fig. 1. Zook's lunar ejecta environment gives a ratio between the ejecta flux and the incident meteoroid flux ( $\sim 10^4$ ) comparable to Gault and Shoemaker's.

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<sup>1</sup> The values Orrok was working with were so uncertain at the time that he could not exclude the possibility that the ejecta penetration rate could be as large as 28 times the sporadic meteoroid penetration rate or as small as 0.07 times the sporadic rate.

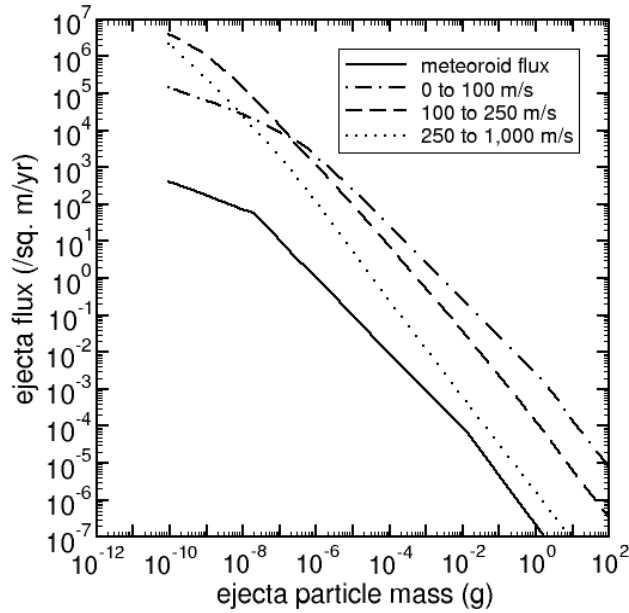


Fig. 1 Zook's cumulative ejecta flux environment.

The NASA SP-8013 meteoroid environment [7] released in 1969 contains a more widely known model of the lunar ejecta environment. The author of NASA SP-8013 implies that he derived his flux curves from Zook's by factoring the fluxes down by the ratio of the NASA SP-8013 to Zook's sporadic meteoroid fluxes and extrapolating the 1 to 100 g dependence to all ejecta particle masses. NASA-SP-8013 does not list the upper size limit of ejecta particles in the model. The authors chose to plot Fig. 1 with masses up to 100 g.

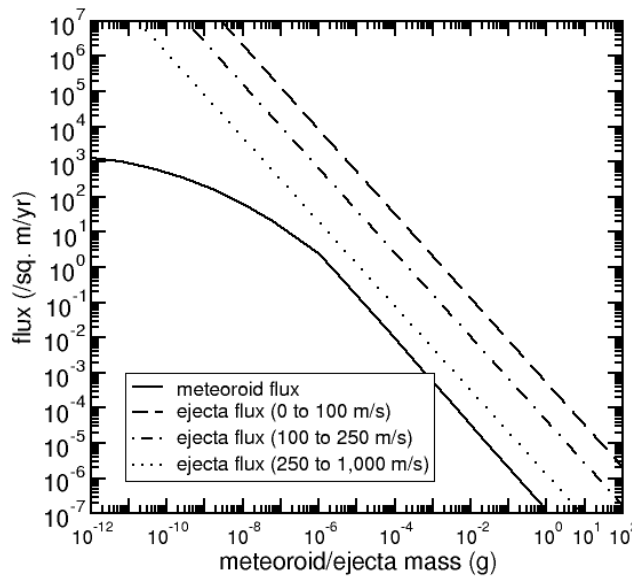


Fig. 2 NASA SP-8013 cumulative ejecta flux environment.

The most recent reference that the authors have seen on the risk of perforation by lunar ejecta is Humes and Bess' [8] 1972 analysis. They calculated the risk of perforation by lunar ejecta using Zook's procedure and the meteoroid environment of NASA SP-8013 and concluded that the risk of perforation of a single sheet of aluminum by ejecta was a factor of 250 less than the risk from the sporadic meteoroid flux. However, due to the relatively poor low speed performance of aluminum meteoroid bumpers, they found that the risk of perforation of a bumper protected aluminum structure by ejecta was comparable to the risk from perforation by the incident sporadic meteoroid flux. Eardley [5] obtained the same result obtained in 1966.

As far as the authors know, an astronaut's risk of impact by lunar ejecta has not been re-examined since Apollo. Intervening research has revised two significant parameters of the original analysis since that time though, prompting this reanalysis of the risk. Because of Apollo, we now know that a fine soil layer to a depth of 5 to 10 meters in the lunar maria and a depth of 20 to 30 meters in the lunar highlands covers the lunar surface. The distribution of soil particle diameters is restricted to a small range with an average particle size of 80 to 100 microns. Thus, the maximum mass ejecta particle ever likely to strike an astronaut is smaller than one would expect if the lunar surface were solid basalt. Second, scaled laboratory ejecta studies show that the ejecta speed distribution from the cratering impact of a soil target is biased towards smaller speeds than the distribution of speeds from the cratering of a basalt target. Thus, the risk of perforation will be smaller than the NASA SP-8013 estimate.

In what follows we develop in section 2 the relation for the cumulative distribution of the total mass of ejecta particles with speed larger than  $v$  that arrive at a location as the result of a sporadic meteoroid impact distance  $r$  away. In section 3, the authors specialize the ejecta flux equation derived in section 2 to the case of sporadic meteoroid impacts into the lunar soil layer. The authors apply these results in section 4 to the assessment of an astronaut's risk of space suit perforation by an ejecta particle during lunar EVA.

### 3 EJECTA FLUX FROM THE SPORADIC METEOROID FLUX

The authors calculate the ejecta flux  $F^+$  by first calculating the ejecta mass per unit area  $\mathcal{M}^+$  that lands at the reference point because of the sporadic meteoroid flux impacting the lunar surface. If we define  $k(m_e) dm_e$  as the increment of ejecta mass per unit area having masses in the range  $[m_e, m_e+dm_e]$ , then  $\mathcal{M}^+ k(m_e) dm_e$  is the mass per unit area of ejecta at the reference point with ejecta particle masses in the range  $[m_e, m_e+dm_e]$ . The increment of flux  $dF^+$  of ejecta particles with masses in the range  $[m_e, m_e+dm_e]$  is then calculated by dividing the total mass per unit area of particles with mass  $m_e$  by the particle mass  $m_e$  to get the flux of particles with that mass, i.e.  $\mathcal{M}^+/m_e k(m_e) dm_e$ .

The first step towards calculating the ejecta mass per unit area  $\mathcal{M}^+$  from the whole meteoroid environment is to calculate the mass per unit area  $\mathcal{M}$  that lands at the reference point from a single meteoroid impact. Housen et al [9] demonstrated that the total mass excavated from a crater and launched at speed  $v$  or larger,  $M(>v)$ , is a power-law of the crater dimensions. One can manipulate that relation into the form shown below as Eq. (1),

$$\frac{M(>v)}{m} = K \left( \frac{v}{U} \right)^{-B}, \quad (1)$$

where  $m$  is the mass of the meteoroid striking with speed  $U$  and whose trajectory makes an angle  $\psi = 0$  degrees with respect to the normal to surface of the Moon<sup>2</sup>. The equations of exterior ballistics give a one-to-one mapping from launch speed to distance ejected,  $r$ , hence all of the crater ejecta launched at speed  $v$  or larger lands at distance  $r$  or larger from the crater. Thus Eq. (1) can also be thought of as the cumulative mass which lands at a distance  $r$  or greater from the impact.

An incremental amount of ejecta mass from a normal impact spreads over the area of the incrementally wide annulus  $2\pi r dr$ . So the mass per unit area,  $\mathcal{M}$ , that lands at distance  $r$  from the crater is,

$$\mathcal{M} = \frac{dM}{2\pi r dr}, \quad (2)$$

the desired relation.

Next, we calculate the total ejecta mass per unit area landing at the reference point from all of the sporadic meteoroid impacts occurring around the reference point. Call the total mass of ejecta particles per unit area per unit time that originate from distance  $r$  or larger from the reference point  $\mathcal{M}^+$ . We simplify the calculation by assuming

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<sup>2</sup> Housen has determined the fit parameters to Eq. (1) for sand,  $K=0.020$  and  $B=1.2$ , and for basalt,  $K=0.065$  and  $B=1.65$ , when the meteoroid mass density is  $1.0 \text{ g/cm}^3$  [10].

that the meteoroid environment is approximated by a flux of particles all traveling at a single speed  $\langle U \rangle$  and all impacting the lunar surface at angle  $\psi = 0$  degrees. Thus,  $\mathcal{M}^+$  is solved for by integrating over all meteoroid impacts that occur at distance  $r$  with mass between  $m$  and  $m+dm$ ; that is,

$$\mathcal{M}^+ = \int_r^\infty \int_{m_0}^\infty 2\pi r \mathcal{M} n(m) dm dr, \quad (3)$$

where  $n(m) dm$  is the number of sporadic meteoroid impacts per unit area per unit time with masses in the range  $[m, m+dm]$ . We will use the negative of the derivative of the Grün et al [11] sporadic meteoroid flux for  $n(m)$ . The variable limits of integration are  $m_0$  which is the minimum mass sporadic meteoroid that will launch ejecta with speed  $v$  or larger, and  $r$  is the minimum range from the reference point from which ejecta particles can originate and still impact the reference point at speeds of  $v$  or larger. Now substitute Eq. (2) into Eq. (3) making the change of variable from  $r$  to  $M$  to get,

$$\mathcal{M}^+ = \int_{M_0}^0 \int_{m_0}^\infty n(m) dm dM. \quad (4)$$

The lower limit of integration on the outer integral,  $M_0$ , is the cumulative ejecta mass that arrives from distance  $r$ . The upper limit of integration is the cumulative ejecta mass that arrives from infinitely far away and is identically zero for all impacting meteoroid masses.

To obtain a flux, we need to convert the increment of ejecta mass  $dM$  arriving from distance  $[r, r+dr]$  away to an increment of number of particles. If the increment of ejecta mass  $dM$  has the distribution of ejecta particle mass  $k(m_e) dm_e$  then the number of particles with masses between  $[m_e, m_e+dm_e]$  is  $dN = dM/m_e k(m_e) dm_e$ . Therefore, the flux of ejecta particles landing at the point of reference from sporadic meteoroid impacts at all surrounding locations is,

$$F^+ = \int_{M_0}^0 \int_{m_0}^\infty \int_{m_e}^{m_e^*} \frac{k(m_e, \dots)}{m_e} n(m) dm_e dm dM. \quad (5)$$

The ellipse in the distribution of ejecta particle masses indicates that in general the distribution may depend on parameters other than  $m_e$ , such as  $v$ ,  $m$ ,  $\langle U \rangle$  and  $\psi$ . The lunar soil number-fraction density function is integrated from the desired ejecta mass  $m_e$  to the maximum mass ejecta particle,  $m_e^*$ , that can be launched from the impact crater produced by a meteoroid with mass  $m$  and speed  $\langle U \rangle$ .

Finally, make a change of variable from  $M$  to  $v$  by substituting Eq. (1) into Eq. (5) to obtain the following equation in ejecta speed,

$$F^+ = \frac{KB}{\langle U \rangle} \int_v^\infty \int_{m_0}^\infty \int_{m_e}^{m_e^*} \frac{k(m_e, \dots)}{m_e} \left( \frac{v}{\langle U \rangle} \right)^{-B-1} m n(m) dm_e dm dv. \quad (6)$$

Section 4 contains the specialization of Equation (6) to the case of ejecta flux from sporadic meteoroid impacts into lunar soil.

#### 4 EJECTA FLUX FROM SPORADIC METEOROID IMPACTS INTO THE LUNAR SOIL

The key assumption enabling a calculation of the ejecta flux from sporadic meteoroid impacts into the lunar soil is that every increment of ejecta mass  $dM$  is assumed composed of the same distribution of particle sizes  $k(m_e) dm_e$  characterizing the lunar surface. To be sure, the impact sorts the blocks ejected from large craters by size, i.e., large blocks land close by the crater and smaller blocks travel further. However, this mechanism does not apply to the smaller cratering events under consideration here. The block sorting comes about when the meteoroid is large enough to penetrate the soil layer and excavate the bedrock below. The bedrock close to the point of impact sees the

largest stresses and gets broken into the smallest pieces. The impact launches the blocks closest to the point of impact the greatest distance; hence, the impact launches the smallest blocks the greatest distance. Hörz and coworkers [12] have measured the comminution and agglutination of soils in laboratory impacts and have concluded that the comminution rate decreases with the number of re-impacts and the agglutination is 1 wt% or less of a high speed impact. The implication here is that a single impact producing a crater 10 m or smaller in diameter will not alter the distribution of soil particle sizes significantly. Hence we'll drop the ellipse from  $k(m_e)$  in Eq. (6).

Besides assuming an ejecta size distribution we also need to make specific assumptions about the limits of integration. The only requirement on the upper limit of integration over the ejecta particle mass,  $m_e^*$ , that we know of is that it must be smaller than the crater size, let's say by some fixed ratio  $k_3$  of the excavated crater mass; that is  $m_e^* = k_3 \rho V$ . We use the crater volume relation from [13],  $V = 1,130 m^{0.83} U^{1.02}$ , for sand targets and the Moon's acceleration due to gravity. The volume  $V$  is in cubic centimeters, the meteoroid mass  $m$  is in grams and the impact speed  $U$  is in km/s. We will assume that the mass density of the lunar soil is  $1.8 \text{ g/cm}^3$ , which is on the high end of the values from the Apollo core samples which varied from  $1.2$  to  $1.9 \text{ g/cm}^3$  [14]. The lower limit of integration over the meteoroid mass,  $m_0$ , is the smallest mass sporadic meteoroid traveling at speed  $\langle U \rangle$  and impacting at  $\psi = 0$  degrees that will launch an ejecta particle of mass  $m_e$  or larger with speed  $v$  or larger. Again, we require that the crater must be larger than the ejecta particle before the impact launches the particle. Let's use the prior criterion of a fixed ratio of the excavated crater mass; that is  $m_0 = m_e / (k_3 \rho V)$ .

One now needs a relation for  $k(m_e)$  to solve the double integral. Reference [14] is a review of measured lunar soil distributions. The distribution of lunar soil particle diameters<sup>3</sup> is given in [14] in terms of the parameter  $\phi$  where,

$$\phi = -\log_2 d = -\frac{\log_{10} d}{\log_{10} 2 \text{ mm}}, \quad (7)$$

and the soil particle diameter  $d$  is in mm. The lunar soil particle size distributions are typically normal in  $\phi$ , hence the fraction of the soil sample mass with soil particles diameters between  $[\phi, \phi+d\phi]$  is given by the relation,

$$h(\phi)d\phi = d\phi \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-(\phi - M)^2 / 2\sigma^2\right), \quad (8)$$

where  $h(\phi)$  is unit less and the standard deviation  $\sigma$  ranges from 1.99 to 3.73 and the mean value  $M$  ranges from 3.32 to 4.48. McKay (as quoted in [14]) has shown that  $\sigma$  and  $M$  are distributed about the line  $\sigma = 5.26 - 0.76M$ , where the most mature (comminuted) soils have the largest value of  $M$ . In what follows, we shall use  $M = 3.5$  and  $\sigma = 2.6$  as typical of an immature soil, hence coarser than much of the lunar surface. Making a change of variable from  $\phi$  to the diameter  $d$  results in,

$$j(d)dd = \frac{1.4427}{d} dd \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-(-3.3219 \log d - M)^2 / 2\sigma^2\right], \quad (9)$$

where  $d$  is in mm and  $j(d) dd$  is the fraction of ejecta with diameters between  $[d, d+dd]$  and  $j(d)$  has units of  $1/\text{cm}$ .

Integrating  $j(d)$  from  $d$  to very large sizes gives the number of soil particles with diameter  $d$  or larger,  $N(>d)$ . The result of this integration is plotted in Fig. 3 for values of  $\sigma = 2.6$  and  $M = 3.5$ .

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<sup>3</sup> This not strictly a number distribution. It is the fraction of the soil sample mass with diameter  $>d$ . One determines it sieving the soil sample and then weighing what remains in the sieve and dividing by the initial mass.

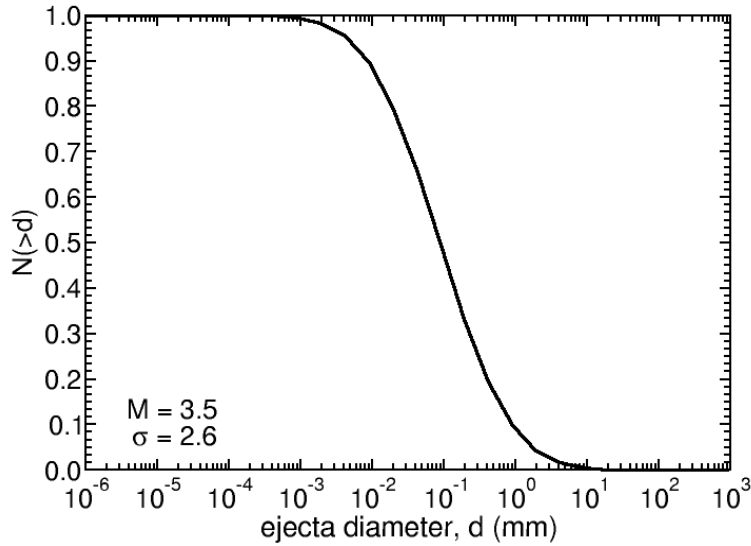


Fig. 3. Cumulative number distribution of particle sizes for typical lunar soil.

Note that some 90% of the soil particles are smaller than 1 mm as indicated on page 287 of [14].

Making a change in variable from  $d$  to  $m_e$  in Eq. (9) and substituting the result into Eq. (6) and performing the triple integral numerically gives Fig. 4: a cross plot of the ejecta flux with the sporadic meteoroid flux at the surface of the Moon. Compare Fig. 4 with the previous estimates of the ejecta flux in Figs. 1 and 2. Note that the ejecta flux estimated here is smaller than both Zook's and the NASA SP-8013 ejecta environments. (Four orders of magnitude smaller at 1 g ejecta mass.)

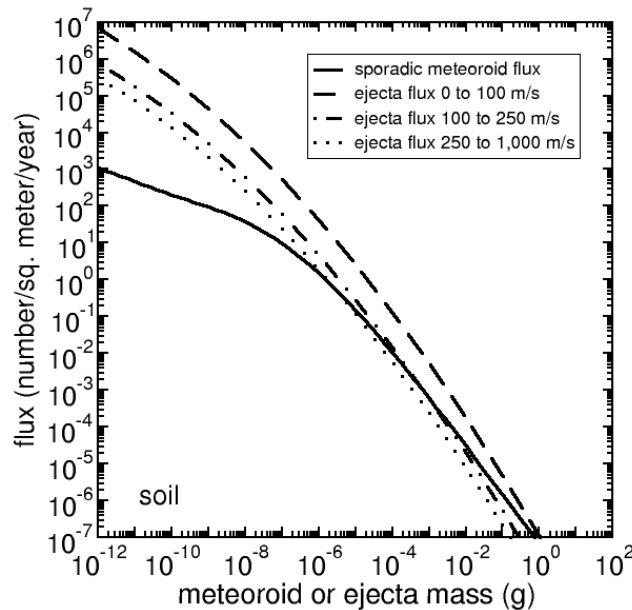


Fig. 4. Ejecta flux from impacts of the lunar surface soil layer.

The authors performed a parameter study to determine the sensitivity of the results to  $\langle U \rangle$  and  $k_3$ . They found that if one varied  $\langle U \rangle$  from 20 km/s to 30 km/s that the flux changed by  $\pm 25\%$ . Furthermore, if one varied  $k_3$  from 0.00002 to 0.2 (the value Zook used for basalt) that the results did not change for ejecta masses less than 10  $\mu\text{g}$ . However, if one increased  $k_3$  to 0.2, then the flux of 1 g ejecta particles increased by a factor of four and if one decreased  $k_3$  to 0.00002, then the flux of 1 g ejecta particles increased by a factor of six.

## 5 RISK OF CRITICAL IMPACT BY EJECTA FROM THE SPORADIC METEOROID FLUX

Assume that when the ejecta particle's kinetic energy exceeds a critical value,  $E_c$  the particle will perforate a spacesuit. McAllum [15] reported a design value of 1.7 J for the Gemini space suit and Christiansen, Cour-Palais and Friesen [16] measured values of 50 to 90 J for the Shuttle/ISS space suit. Now parameterize the results over this range of critical energies.

One can now use the critical impact energy to determine the lower bound on the integration over ejecta mass; i.e.  $m_e = 2 E_c / v^2$  and the lower limit on the integration over meteoroid mass  $m_0 = [2 E_c v^2 / (k_3 \rho 1,130 U^{1.02})]^{1/1.83}$  computed from the crater volume scaling relation. The upper limit on ejecta mass remains our previous estimate based on using a fraction of the excavated crater mass. As for the limits on the integration over ejecta speed, it seems reasonable to assume that there is a minimum speed below which the ejecta impact is more of a structural response than a penetration event. Suit designers have not measured this speed. The authors set this minimum impact speed,  $v_{min}$ , to 100 m/s. They found the soil results to be insensitive to values from 20 to 100 m/s but the basalt results decreased by a factor of 16 when they changed  $v_{min}$  from 20 to 100 m/s. The maximum impact speed will be escape speed at the surface of the moon: about 2.4 km/s.

Substituting the above limits of integration into Eq. (6) and numerically integrating resulted in Fig. 5. The results were plotted over a range of critical energies from 1 to 100 Joules and for the typical values of the lunar soil size distribution parameters  $M$  and  $\sigma$ .

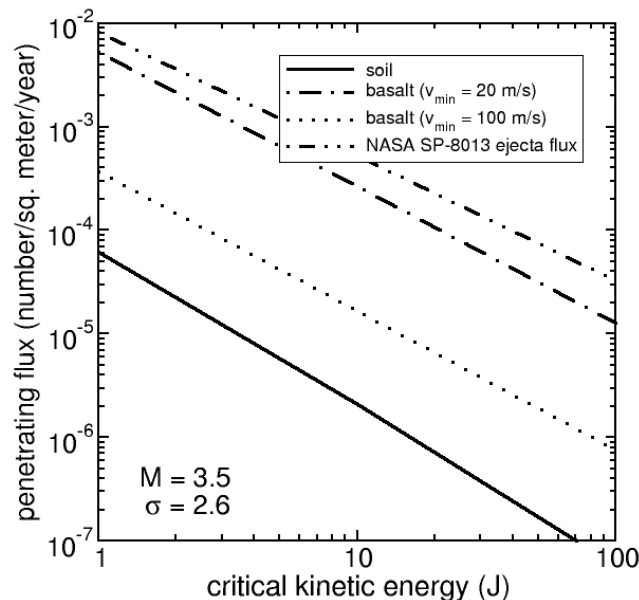


Fig. 5. Penetrating flux as a function of critical energy for penetration and lunar soil size-distribution parameters.

Figure 5 shows that the risk of suit penetration is a factor of 6 to 12 smaller for ejecta originating from the soil layer than for ejecta originating from basalt. We can also use Fig. (5) to estimate the mean time to failure due to lunar ejecta provided we know the area of the space suit, its ballistic limit energy, and that no areas of the suit are redundant. The surface area of Apollo lunar space suit was in the range of 3 to 3.5 square meters. If a modern lunar space suit, with 3.5 square meters surface area, is hardened to 50 J ballistic limit energy, then the mean time to failure due to lunar ejecta is 1,700,000 yrs for the typical soil distribution. Compare this with 3,800 years mean time to failure calculated using the NASA SP-8013 procedure.

Figure 5 also plots the estimates of risk of perforation by ejecta from a basalt surface when the lower limit on penetration speed is dropped from 100 m/s to 20 m/s. Note that the penetrating flux calculated with  $v_{min} = 20$  m/s is a factor of 16 larger than the penetrating flux calculated with  $v_{min} = 100$  m/s. This is a direct result of the large numbers of large particles characteristic of impacts into basalt. The large particles can penetrate at small speeds and therefore make the most significant contribution to the risk. A parameter study showed that more than 50% of perforating impacts occurred for basalt ejecta particles traveling between 20 and 30 m/s and that 90% of the



perforating impacts occurred from particles traveling between 20 and 70 m/s. This makes the ballistic limit velocity the controlling factor in an assessment of the risk from basalt ejecta.

## 6 CONCLUSIONS

The composition of the lunar surface makes a significant difference to assessments of risk of perforating impact from lunar ejecta. Previous authors based their estimates on the lunar surface being composed of basalt. The actual lunar surface is a very fine soil which when impacted by meteoroids produces slower speed ejecta with finer size particles than basalt. Thus, the prior estimates of the risk of penetration by lunar ejecta have overestimated the risk by two orders of magnitude and have the added feature of sensitivity to the assumed lower bounds on ballistic limit velocity.

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