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USE OF RAW MARTIAN AND LUNAR SOILS FOR SURFACE-BASED REACTOR SHIELDING

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USE OF RAW MARTIAN AND LUNAR SOILS FOR SURFACE-BASED REACTOR SHIELDING

by

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Report

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DEDICATION

I would like to dedicate this work to my wife Tatiana and our son Michael, who had to endure with me my academic struggles. We have finally arrived, and now we look forward to the years to come.

ACKNOWLEDGEMENT

My gratitude is to my academic supervisor, Dr. Sheldon Landsberger and to Dr. Steven Biegalski for your advice and guidance through all these years. I'm also grateful for all the support that your staff and faculty provided me as a distance learner, by going the extra mile to accommodate my hectic schedule. Both Drs. Landsberger and Biegalski are faculty members of the University of Texas at Austin, Mechanical Engineering Department (Nuclear and Radiation Engineering Program).

I would also like to thank Dr. Sukesh Aghara, from the NASA Center for Applied Radiation Research, Chemical Engineering Department, Prairie View A&M University, Prairie View, TX. This work is work is largely based on an earlier unpublished effort that I performed as a graduate student under his guidance.[1]

[1] The original unpublished work was entitled "Neutron Activation Characteristics of Martian and Lunar Soils", and it was intended to be published under Proceedings of the Space Nuclear Conference 2005, San Diego, California, June 5-9, 2005, Paper 1134. Those findings were never published. This current effort builds on that original work.

USE OF RAW MARTIAN AND LUNAR SOILS FOR SURFACE-BASED REACTOR SHIELDING.

by

Jose L. Christian, Jr. M.S.E.
The University of Texas at Austin, 2010

SUPERVISOR: Sheldon Landsbeger

For several decades, the idea of flying and landing a less-than-man-rated nuclear reactor for planetary surface applications has been considered. This approach promises significant mass savings and therefore reduction in launch cost. To compensate for the lack of shielding, it has been suggested the use of in-situ materials for providing radiation protection. This would take the form of either raw dirt walls or processed soil materials into blocks or tile elements. As a first step in determining the suitability of this approach, it is necessary to understand the neutron activation characteristics of these soils. A simple assessment of these activation characteristics was conducted for both Martian and Lunar soils using ORIGEN2.2. An average composition for these soils was assumed. As a baseline material, commonly used NBS-03 concrete was compared against the soils. Preliminary results indicate that over 2.5 times more γ-radiation production of these soils vs. concrete took place during the irradiation phase (a baseline of 2.4×10^{11} neutrons/sec-cm^2 was assumed). This was due primarily to radiative capture on Na^{23} and Mn^{55} and

subsequent decay of their activation products. This is does not necessarily disqualify these materials as potential shielding material since the γ-radiation output was only in the order of 4.2×10^8 photons/cm^3-sec. Furthermore, these soils did not show any significant activity after shutdown of the neutron source (the reactor), since all activation products had very short half lives. Their performance in this area was comparable to that of NBS-03 concrete.

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INTRODUCTION

In the past three decades, NASA has contemplated the use of nuclear reactors for space transportation, as well as surface based reactors to power habitats and surface operation equipment. Since radiation shielding is one of the largest mass components of such system, shield optimization is always the first item of consideration.

To reduce shielding mass, concepts utilizing less than man rated shields ("naked reactors") have been studied. For surface applications, distance ($1/R^2$) and in-situ materials are used to provide shielding to habitats. In either case, the local surface soil is expected to be irradiated with substantial neutron and gamma flux. Therefore, if a naked reactor concept is to be considered for surface applications, it is important to consider the reactor-soil interaction as well.

High activation characteristics of the soil would require condemnation of area surrounding the reactor site even long after the reactor has been pulled off line or the landing vehicle have left the area. This scenario is unacceptable. However, a soil with low activation characteristics would allow for a more environmentally friendly interaction as well as providing the capability of utilizing local soil as shielding material, by erecting walls around the reactor or utilizing local geological features (such as dunes or craters) for shielding.

Many factors need to be taken into account for assessing the suitability of these soils for reactor radiation shielding. Because the extent of this effort, we will only concentrate on assessing the neutron activation characteristics of these soils. ORIGEN 2.2 was the tool chosen to conduct this assessment.

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1.0 BUILDING THE MODEL

The first item in our model that needed definition was the soil characteristics of both Mars and the Moon. Although it is understood the rich and varied composition of both soils and their geographical variations, an average planetary soil composition will be used for each case.**[1], [2], [3]**

For basis of comparison, we decide to use one of the most common types of concrete in nuclear power plants facilities; NBS-03 Concrete.[**4]** When looking at table 1, the first characteristic that stands out is that this type of concrete has a lower metallic content than the average Lunar or the Mars soils. This is especially true for iron, where for concrete, it consist of 1.1% per weight, as opposed to Martian (15.8%) and Lunar (8.1%) soils.

Table 1: Mars and Lunar soil characteristics in comparison to NBS-03 concrete.

		Concentrations (g/cm^3)			W/O		
Z	Elements	Lunar	Mars	NBS-03 Concrete	Lunar	Mars	NBS-03 Concrete
1	H			0.0200			0.85%
6	C			0.1180			5.01%
8	O	0.7230	0.9049	1.1160	48.21%	42.97%	47.35%
11	Na	0.0326	0.0157		2.17%	0.74%	
12	Mg	0.0767	0.0895	0.0570	5.12%	4.25%	2.42%
13	Al	0.0621	0.0744	0.0850	4.14%	3.53%	3.61%
14	Si	0.3421	0.4915	0.3420	22.81%	23.34%	14.51%
15	P	0.0043	0.0039		0.29%	0.18%	
16	S		0.0232	0.0070		1.10%	0.30%
17	Cl		0.0054			0.26%	
19	K	0.0101	0.0087	0.0040	0.67%	0.41%	0.17%
20	Ca	0.1119	0.1304	0.5820	7.46%	6.19%	24.69%
22	Ti	0.0131	0.0215		0.88%	1.02%	
25	Mn	0.0022	0.0037		0.15%	0.18%	
26	Fe	0.1215	0.3328	0.0260	8.10%	15.81%	1.10%

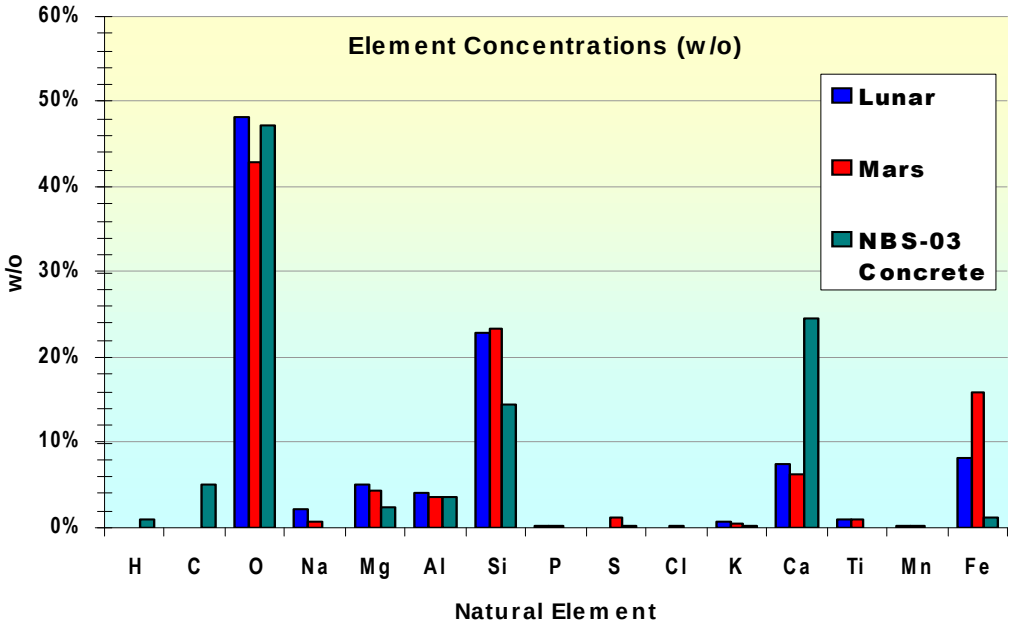

Figure 1: Graphical comparison of elemental constituents of Martian and Lunar soils

Another interesting comparison is the content of water in concrete. The average Lunar and Mars soils are devoid of hydrogen, although that is speculative at this point. For the sake of this analysis, the soils were assumed totally dry. In this case of Mars, we will study in the future the effect of water content in its soil. Figure 1 provides a visual representation of element composition for all three materials analyzed.

The next parameter we defined in our ORIGEN 2.2 model was the neutron flux. In actuality, the neutron flux and its energy spectrum will be determined by the type and size of reactor deployed, as well as the amount of shielding used. At this point NASA has not baselined the design of any reactor for surface operations.

A flux of 2.4×10^{11} netrons/cm^2-sec was used, which can achieved as a typical output the $1MW_{th}$ TRIGA reactor at University of Texas, at Austin. The rationale being that we could later reproduce or validate the results of this study with empirical data after performing a soil irradiation test using this type of reactor. The details of this test will not be discussed in this report or the additional upgrades to this model.

```
-1
-1
-1
   RDA  * * * * * * * * * * * * * * * * * * * * * * * * * * *
   RDA     Calculation of Mars soil activation assuming
   RDA     neutron flux equivalent to UT TRIGA (~ 1MWth)
   RDA     research reactor
   RDA  * * * * * * * * * * * * * * * * * * * * * * * * * * *
   RDA
   RDA  LIBRARIES: Light, Actinides and Fission Products
   RDA             Decay lib.    xsect lib     controls
   LIB       0     1  0  0       201  202  203   9 0 0 1 0
   RDA  Photon Lib: Activation, Actinide, Fission Products
   PHO              101 000 000   10
   INP  1   1  -1  -1   1   1
   OPTL 8 8 8 8 3 8 3 3 8 8 3 3 8 8 8 8 8 8 8 8 8 8 8 8 8 1 8
   OPTA 8 8 8 8 3 8 3 3 8 8 3 3 8 8 8 8 8 8 8 8 8 8 8 8 8 1 8
   OPTF 8 8 8 8 3 8 3 3 8 8 3 3 8 8 8 8 8 8 8 8 8 8 8 8 8 1 8
   RDA
   RDA  * * * * * * * * * * * * * * * * * * * * * * * * * * *
   RDA     Irradiate Material for 1 year
   RDA
   RDA  * * * * * * * * * * * * * * * * * * * * * * * * * * *
   HED  1 Initial Concentration
   BUP
   IRF  100  2.40E11 1 2 4 2
   IRF  200  2.40E11 2 3 4 0
   IRF  365  2.40E11 3 4 4 0
   BUP
   RDA
   RDA   Take material irradiated for 1 year and let it
   RDA   decay for 1, 3, 5 and 10 years
   DEC   1  4 5  5 1
   DEC   3  5 6  5 0
   DEC   5  6 7  5 0
   DEC   10 7 8  5 0
   RDA
   OUT  8   1  -1   0
   END
  4 250000 0.0037  150000  0.0039  170000 0.0054 0  0.0
  4 190000 0.0087  110000  0.0157  220000 0.0215 0  0.0
  4 160000 0.0235  130000  0.0744  120000 0.0895 0  0.0
```

Figure 2: ORIGEN2.2 code for Martian soil analysis.

Since we do not know the mission profile either, i.e. the amount of time the reactor will operate on the surface, we will assume the reactor will operate for one year, irradiating the soil at the flux earlier prescribed, and then it will be shut down. During the year of operation (build-up), photon emissions will be calculated due to radiative capture (***n***,**γ**) and activation products decay. After this irradiation phase, the material will be let decayed, and calculate remaining activity after one three, five and ten years after shutdown. This analysis is performed for all three materials. A sample input of the ORIGEN2.2 is shown in figure 2.

It is important to understand the relevance of the assumptions made up to this point, with respect to real-life mission scenarios. Since the purpose of this study is to determine the feasibility of using raw Martian and Lunar soils for reactor shielding, we could prove this feasibility in terms of relative performance with respect to NBS-03 concrete. For absolute performance of any of these materials, then specifics of the mission architecture and reactor design will be required, in addition to actual characteristics of the soil at the landing site.

The code shown in figure 2 is flexible enough to allow for changes in the material composition, neutron flux, irradiation and decay times. This will be useful when architecture parameters emerge, as mission objectives get defined.

2.0 DISCUSSION OF RESULTS

The first results we obtain are from photon production, as shown in figure 3. The first characteristic to notice is the response similarity of the Mars and Lunar soils. During the irradiation phase, the curve remained flat for all three examples. The Mars and Lunar photon production through irradiation was 4.22 x 10^8 and 4.43 x 10^8 photons /cm^3-sec, respectively. For the NBS-03 concrete it was 1.24 x 10^8 photons /cm^3-sec. This translates into the Mars and Lunar soils performing > 2.5 times worse than the concrete, in terms of photon emissions. After the irradiation cycle is completed, the emissions

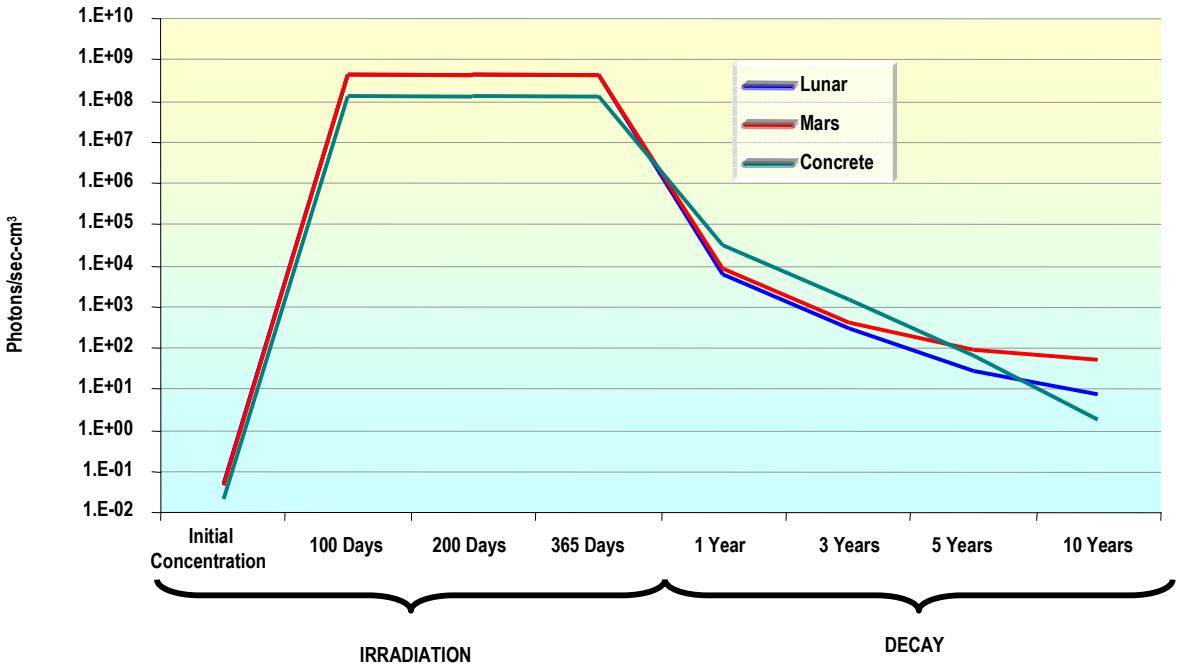

Figure 3: Photon production

decrease about four orders of magnitude within the first year, and another four orders of magnitude for the following nine years. This can be interpreted as some neutron captures **(n,γ)** taking place during irradiation (as the dominant reaction), and then followed by a decay of various shorter lived isotopes.

To further understand this process, we need to also understand which mechanisms are at play here. We first start by looking at the photon spectra of all three samples.

2.1 The NBS-03 Concrete

Starting with our baseline, the SBC-03 concrete, we see that (figure 4(a)) that 2 major spikes are visible. The largest one (1.07×10^8 photons /cm^3-sec) occurring around 1.75 MeV, and a minor one occurring at 0.01 MeV with a magnitude of 7.5×10^6 photons /cm^3-sec. The former, being in the γ region is most likely due to radiative captures, while the latter, being in the x-ray region, might be due to either neutron inelastic scattering or electron capture decays from activation products. An interesting detail to observe here is that those "spikes" occur only during the irradiation period, and at the end of it the photon production disappears almost completely (meaning orders of magnitude reduced from maximum). This could be indicative, as we mentioned earlier, of formation of very short lived isotopes that die out soon after irradiation ends (as we inferred earlier from figure 3).

One way to determine what type of activity is taking place, we could refer to figure 4(b) were activation products and its radioactivity (measured in Curies - Ci) were calculated by ORIGEN2.2. The first contributor to radiation we find it to be Al^{28} with 2.83 mCi/cm^3. The most likely parent for this isotope was a neutron capture from Al^{27}, such that:

$$Al^{27} + n \longrightarrow Al^{28} + \gamma \xrightarrow{2.25\text{min}} Si^{28} + \beta^- + \gamma + \bar{\nu}$$

Si^{28} is a stable isotope. Notice that because Al^{28} has such a short half-life (2.25 min) it disintegrates as quickly as it is produced, hence its flat γ response during the build-up (or irradiation) phase. On the other hand, you have a relatively slow build up of Ca^{45} which takes a bit over a year to dissipate and contributes up to 0.93 mCi/cm^3 at its maximum. The most likely scenario for this isotope is another neutron capture from Ca^{44} and the reaction is as follows:

$$Ca^{44} + n \longrightarrow Ca^{45} + \gamma \xrightarrow{162.6\text{days}} Sc^{45} + \beta^- + \gamma + \bar{\nu}$$

Notice that neither of these two isotopes are pure β emitter since this β is also accompanied by a γ. In the case of Al^{28}, this γ is of 1.779 MeV and for Ca^{45} the γ is 12.4 keV (actually this is more in the x-ray regime!). Perhaps these are the lower energy photons that we see at the photon spectrum of this concrete.

Other lesser reactions with modest contributions are:

$$Si^{30} + n \longrightarrow Si^{31} + \gamma \xrightarrow{157.3\ \text{min}} P^{31} + \beta^{-} + \gamma + \bar{\nu}$$

and possibly

$$Ca^{40} + n \longrightarrow Ar^{37} + \alpha^{4}$$

which follows $Ar^{37} \xrightarrow{35\ \text{days}} Cl^{37} + \text{E.C.}(\text{no}\ \ \gamma)$

Also,

$$Ca^{48} + n \longrightarrow Ca^{49} + \gamma \xrightarrow{8.7\ \text{min}} Sc^{49} + \beta^{-} + \gamma + \bar{\nu}$$

$$Sc^{49} \xrightarrow{57.2\ \text{min}} Ti^{49} + \gamma$$

The Ca^{40} reaction is an interesting o\ne, since it's a threshold reaction, requiring neutron of at least 0.9 MeV for the reaction to occur. Neutrons at lower energy levels will most likely produce a radiative capture (***n*,γ**) with Ca^{40} to form Ca^{41}. Ca^{41} has a half life of about 1.03 x 10^5 years. The latter reaction is of no significance to us since Ca^{41} will slowly decay by electron capture (**ε**) and no gamma emissions into K^{41} which is a stable isotope.

Figure 4(a): Photon production spectrum for NBS-03 concrete

Figure 4(b): Activation products for NBS-03 concrete

2.2 Mars Soil

Now, moving to the Mars soil, we could perform a similar analysis. From figure 5(a), we can see that the photon spectrum is quite busy from 1.25 to 3.5 MeV, in addition of those spikes at 0.01 MeV. Since there is a substantial amount of calcium in the Mars soil (about a third of the NBS-03 concrete), perhaps we are still seeing the signature of Ca^{45} decay as well. Another important feature to recognize is that, as in the case of concrete, the photon production drops significantly after irradiation ceases.

The major contributors of radiation are given in figure 5(b). As can be seen Mn^{56} is the one with the biggest response of 3.5 mCi/cm^3. The most likely reaction for producing this isotope was:

$$Mn^{55} + n \longrightarrow Mn^{56} + \gamma \xrightarrow{2.58\ h} Fe^{56} + \beta^- + (3)\gamma + \bar{\nu}$$

Al^{28}, as in the case of concrete, plays also an important role in photon production. The activity for this isotope is 2.48 mCi/cm^3 compared to 2.83 mCi/cm^3 in the case of concrete. An interesting characteristic of this reaction is that the last stage produces three γ's.

Also notice that Na^{24} and Na^{24M} are strong emitters as well with values of 1.4 and 1.1 mCi/cm^3 , respectively. This sodium reaction could be described as follows:

$$Na^{23} + n \longrightarrow Na^{24} + \gamma \xrightarrow{14.96\ h} Mg^{24} + \beta^- + (2)\gamma + \bar{\nu}$$

The metastable state reaction yields to the same isotope of ^{24}Mg but first going through an IT reaction. This decay has a half life on just 20.2 ms.

There are several other lesser reactions that contribute to photon production such as Si^{31}, Ar^{37} and Ca^{45}. These also produce short-lived isotopes through radiative capture, which quickly die out after irradiation ceases. This is with the exception of Fe^{55}. This isotope builds up slowly through the year of irradiation and lingers well into the 10th year after the shut down of the reactor (but at just 50 μCi/cm^3). The reaction for this one is:

$$Fe^{54} + n \longrightarrow Fe^{55} + \gamma \xrightarrow{2.3\ year} Mn^{55} + EC$$

The interesting fact about this reaction is that there are no γ's in the production of Mn^{55}, therefore it should not be much of radiological concern. In the case of NBS-03 concrete Fe is just 1.1% per weight, as opposed to the Martian soil is has in an average 15.8%, hence that activity was not well seen in concrete.

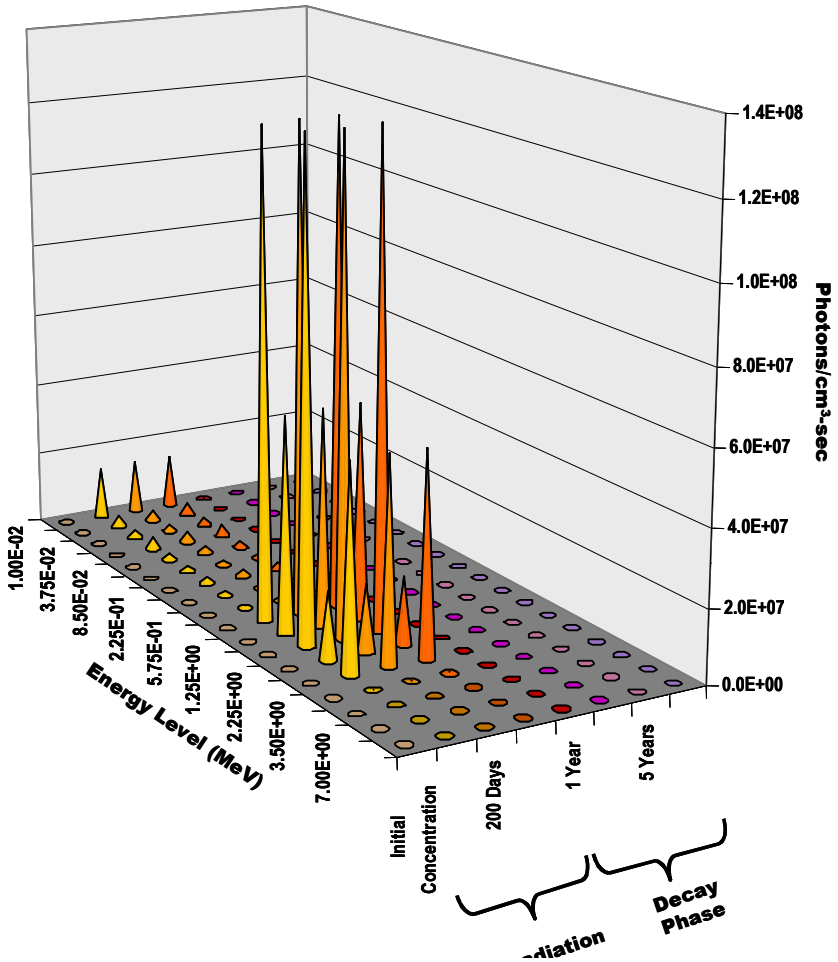

Figure 5(a): Photon production spectrum for Mars soil

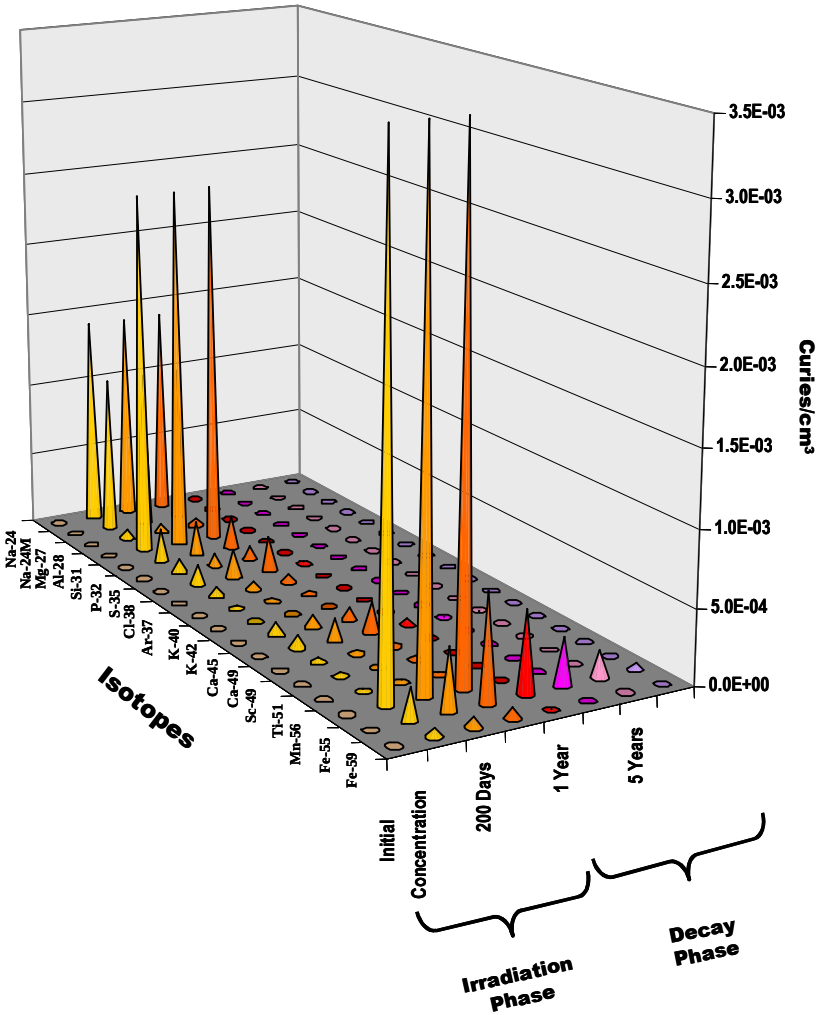

Figure 5(b): Activation products for Mars soil

2.3 The Lunar Soil:

When looking at figure 6(a) for the Lunar soil photon production spectrum and figure 6(b) for the activation product radioactivity, the first thing one notices is the similarity to that of the Martian soil. Indeed, a quick look at table 1, and its evident that both soils contain almost the same elements with the exception of chlorine and phosphorus which apparently are depleted or trace amounts in the Lunar soil. Although iron is abundant on Mars, at a concentration level of 15.8%, the Lunar soil contains 8.1%, hence the similarities in neutron activation characteristics. The slightly higher photon production rates for the Lunar soil could be attributed to the larger concentrations of sodium and aluminum in the Lunar soil with respect to Mars.

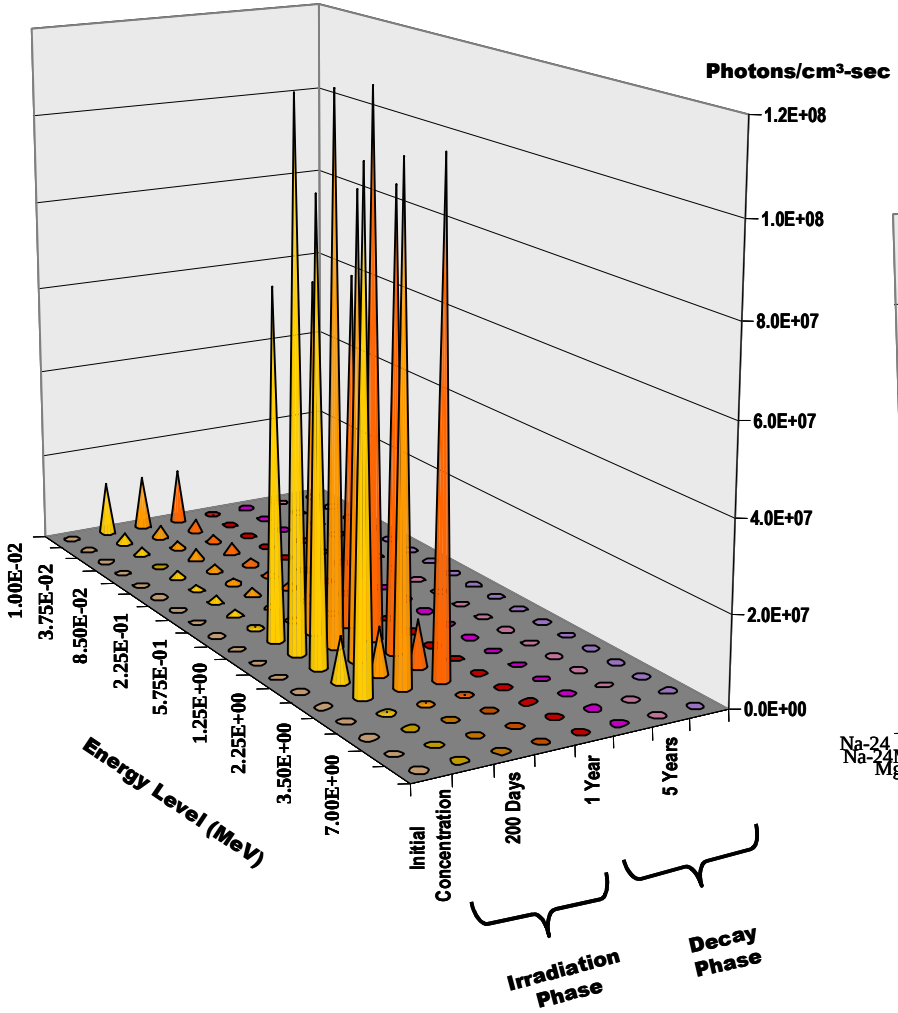

Figure 6(a): Photon production spectrum for Lunar soil

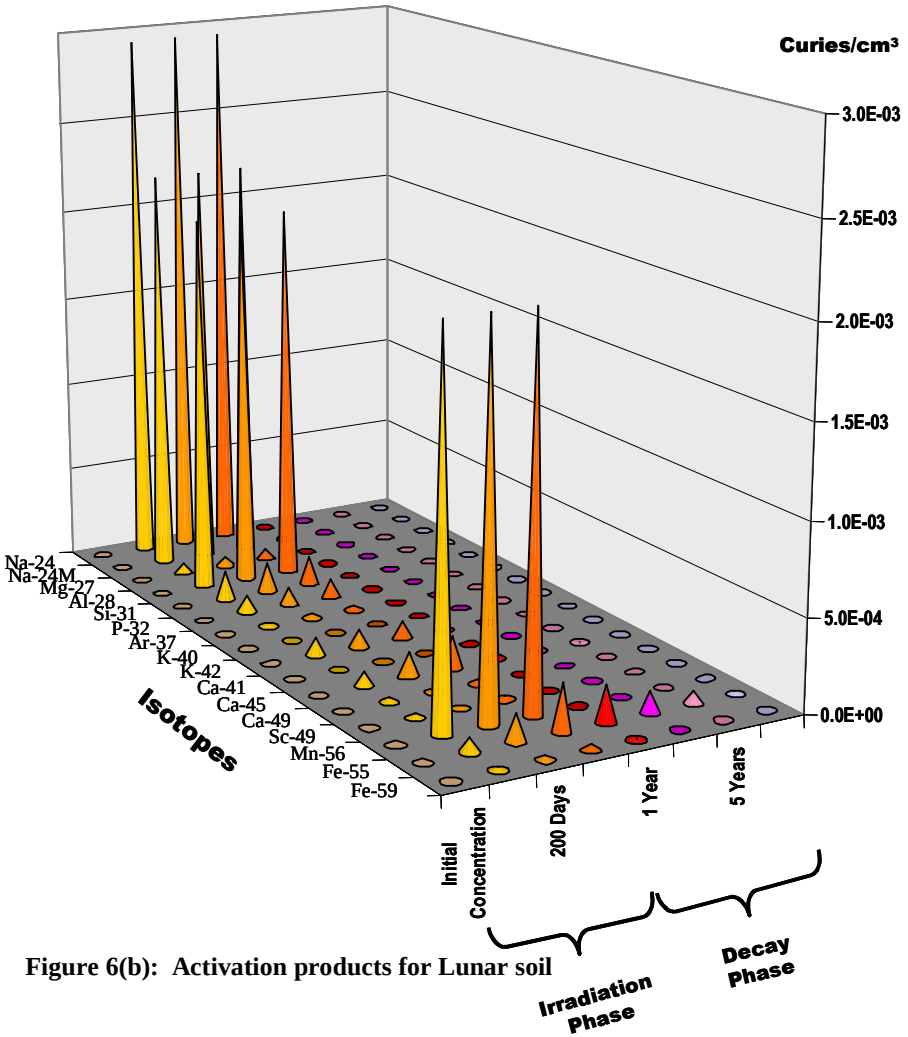

Figure 6(b): Activation products for Lunar soil

3.0 CONCLUSIONS AND RECOMMENDATIONS

Through the use of ORIGEN2.2 and based on current data from both Lunar and Mars average soil composition, we established that for a neutron flux of 2.40×10^{11} neutrons/cm^2-sec, the resulting photon production due to radiative capture and decay of activation products, is somewhat higher than for conventional NBS-03 concrete, under same conditions. The Mars and Lunar the photon production through irradiation was 4.22×10^8 and 4.43×10^8 photons /cm^3-sec respectively, and for the NBS-03 concrete it was 1.24×10^8 photons /cm^3-sec.

This extra activity present in the Lunar and Mars soils could be attributed to the presence of Mn^{55} and Na^{23} since during neutron capture and the following reactions occur:

$$Mn^{55} + n \longrightarrow Mn^{56} + \gamma \xrightarrow{2.58h} Fe^{56} + \beta^- + (3)\gamma + \bar{\nu}$$
$$Na^{23} + n \longrightarrow Na^{24} + \gamma \xrightarrow{14.96\ h} Mg^{24} + \beta^- + (2)\gamma + \bar{\nu}$$

The fact that NBS-03 produces up to 2.5 times less γ's than the other two soils, does not necessary renders them inadequate for radiation shielding. As follow up study, this time utilizing tools such as MCNP, a second radiation transport model can be used to determine other characteristics such as penetration depth of these neutrons (due to reactor

leakage) into the soil before they're stopped and γ-absorption characteristics of the soils as well.

In terms of activation, it was observed that activation products generated on these soils have short half-lives and in essence, from the radiological point of view, these soils pose the same environmental impact as irradiated NBS-03 concrete.

It is important to clarify once more that the chemical compositions of both Mars and the Moon are known in the average at a planetary scale. Nevertheless, localized distributions of other materials beyond those analyzed here could make our conclusion differ significantly, and at the end, those localized soil characteristics are the ones that will determine the true feasibility of the radiation shielding using in-situ materials.

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VITA

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He served as an engineer for over 20 years in the aerospace and nuclear fields, in areas of R&D, systems engineering and program management.

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