Probabilistic Round Trip Contamination Analysis of a Mars Sample Acquisition and Handling Process using Markovian Decompositions

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Abstract—A method for evaluating the probability of a Viable Earth Microorganism (VEM) contaminating a sample during the sample acquisition and handling (SAH) process of a potential future Mars Sample Return mission is developed. A scenario where multiple core samples would be acquired using a rotary percussive coring tool, deployed from an arm on a MER class rover is analyzed. The analysis is conducted in a structured way by decomposing sample acquisition and handling process into a series of discrete time steps, and breaking the physical system into a set of relevant components. At each discrete time step, two key functions are defined: The probability of a VEM being released from each component, and the transport matrix, which represents the probability of VEM transport from one component to another. By defining the expected the number of VEMs on each component at the start of the sampling process, these decompositions allow the expected number of VEMs on each component at each sampling step to be represented as a Markov chain. This formalism provides a rigorous mathematical framework in which to analyze the probability of a VEM entering the sample chain, as well as making the analysis tractable by breaking the process down into small analyzable steps.

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1. INTRODUCTION

Probabilistic round-trip-contamination analysis (PRA), the probability that a Martian sample is contaminated by a Viable Earth Microorganism (VEM) and is then returned to earth during a sample return mission, is of critical importance for a potential future sample return mission. Calculating the probability of a VEM entering into the sample chain is inherently difficult, due to the many components of any sample and handling system, and the corresponding complexity of the sampling and handling sequence. This paper assumes a potential future sample return mission which would not deploy a completely sterile system. Instead it is assumed that critical components of the system (such as the handling system) would be sterile, but other components such as the rover body would be cleaned to a reduced, but not sterile, level of microorganisms. A non-sterile rover would drastically decrease the cost of a potential future mission.

The analysis framework developed here was built while considering an example of an end-to-end sample and handling chain: The Integrated Mars Sample Acquisition and Handling (IMSAH) system concept, currently being developed to provide a possible path forward for a future Mars cashing mission [1]. The IMSAH system includes the complete process of obtaining a rock core sample using a Sample Acquisition Tool (SAT) mounted on a MER class rover, and preparing the samples for potential return to Earth by encapsulating and storing them in a return canister. The IMSAH system concept would consist of a rover arm, referred to as the Tool deployment device (TDD), an arm mounted rotary-percussive coring tool (SAT), and a Sample Handling, Encapsulation and Containerization (SHEC) subsystem.

The goal of this paper is twofold: first, to develop an analysis method for evaluating the PRA of the IMSAH system. This involves analyzing the IMSAH process, providing all possible contamination pathways that a VEM could enter core sample, and evaluating the probability of each of these pathways. Secondly, by creating a rigorous framework for PRA analysis, the limitations and gaps in the current particle release and transport models are considered to provide a road map forward for refining contamination estimates. Because of the limited modeling analysis conducted on some contamination pathways in this paper, the developed analysis framework is the primary product, as opposed to the presented PRA con-

[1] 978-1-4244-3888-4/10/$25.00 ©2010 IEEE.
IEEEAC Paper #1552, Version 2.0, Updated 05/01/2010.

tamination estimates, which should not be regarded as representative.

MoVEMenT, or Markovian VEM Transport, is a new mathematical framework and software implementation developed for evaluating the probability of a Viable Earth Microorganism (VEM) contaminating a sample during the sample acquisition and handling process. MoVEMenT decomposes sample acquisition and handling process into a series of discrete steps or operations, and also breaks the physical system into a set of relevant components. At each discrete time step, two key functions are defined: The probability of a VEM being released from each component, and the transport matrix, which represents the probability of VEM transport from one component to another. By defining the expected the number of VEMs on each component at the start of the sampling process, these decompositions allow the expected number of VEMs on each component at each sampling step to be represented as a Markov chain. The MoVEMenT formalism provides a rigorous mathematical framework in which to analyze the probability of a VEM entering the sample chain, as well as making the analysis tractable by breaking the process down into small analyzable steps.

A significant observation was made in the development of the MoVEMenT framework, and stems from the necessary systems perspective required for this analysis. Researching and producing "conservative" probability estimates of contamination for individual process steps, is not valid and can create 'unconservative' estimates when applied to an entire chain of events. Most previous work considers a single aspect of the entire problem. For instance, considerable work has been done on wind removal and redistribution of particles in various wind speeds. Most of this work takes a "conservative" approach, where assumptions are made which choose the the "worst-case" value, typically resulting in the most number of VEMs being removed. This concept can lead to unintended results when the entire system is considered, illustrated by a simple sequence of a rover drive, followed by in-situ science and sampling. If during the rover drive, the "worst case" assumption is made and 95% of the VEMS on the rover are removed, as opposed to say 50% as given by nominal values, there is now an order of magnitude difference in contamination probability during the sampling stage, as 10 times as many particles remain on the rover. The point here is not that the previous analysis is wrong, but a new perspective needs to be taken when the entire system is considered, and that the assumptions made in previous analysis need to be carefully considered when applied to a sequence of events.

The remainder of this document is structured as follows: Section 2 describes the IMSAH system concept and sample and handling process. Section 3 defines MoVEMenT, the mathematical framework used for analyzing a chain of sampling events. Sections 4 - 9 discuss VEM release and transport mechanisms, relevant to the IMSAH system concept, which are used in assigning probabilities to elements in the MoVEMenT framework. Section 10 then applies MoVEMenT to the IMSAH framework and gives the results of an initial probabilistic analysis of a VEM entering the sample chain during the sample and handling sequence.

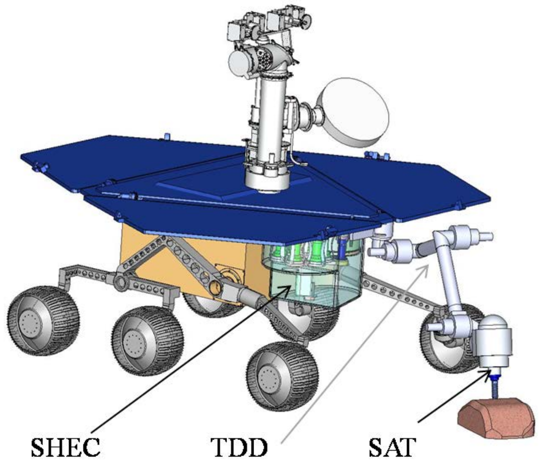

Figure 1. The IMSAH system: Rover, Tool Deployment Device (TDD), Sample Handling Encapsulation and Containment (SHEC) system, and Sample Acquisition Tool (SAT).

2. IMSAH SYSTEM

The Integrated Mars Sample Acquisition and Handling (IMSAH) system is a concept for core sample acquisition and caching with potential application to a Mars caching mission [1] (Figure 1). The concept utilizes a five degree-of-freedom (DOF) Tool Deployment Device (TDD), which deploys a rotary percussive coring tool as well as provides alignment, feed, and preload for the tool. The sample acquisition tool (SAT) provides coring, core break-off, core retention and bit capture and release for bit changeout. A sample is acquired directly into its sample tube in the coring bit assembly (CBA) (Figure 2) and bit changeout is used to transfer the sample to the sample handling encapsulation and caching (SHEC) subsystem where it is sealed and stored.

The CBA including the internal sample tube is shown in Figure 2. The IMSAH system is interesting from a planetary pro-

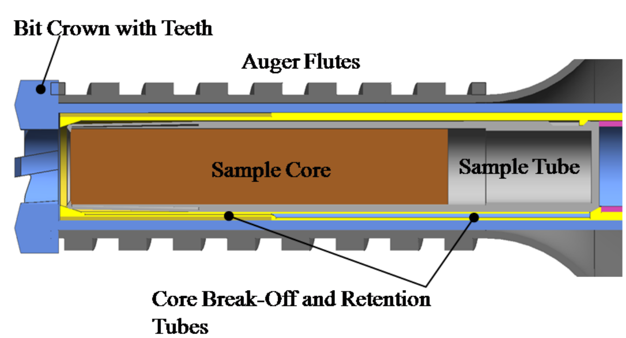

Figure 2. The Core Bit Assembly (CBA)

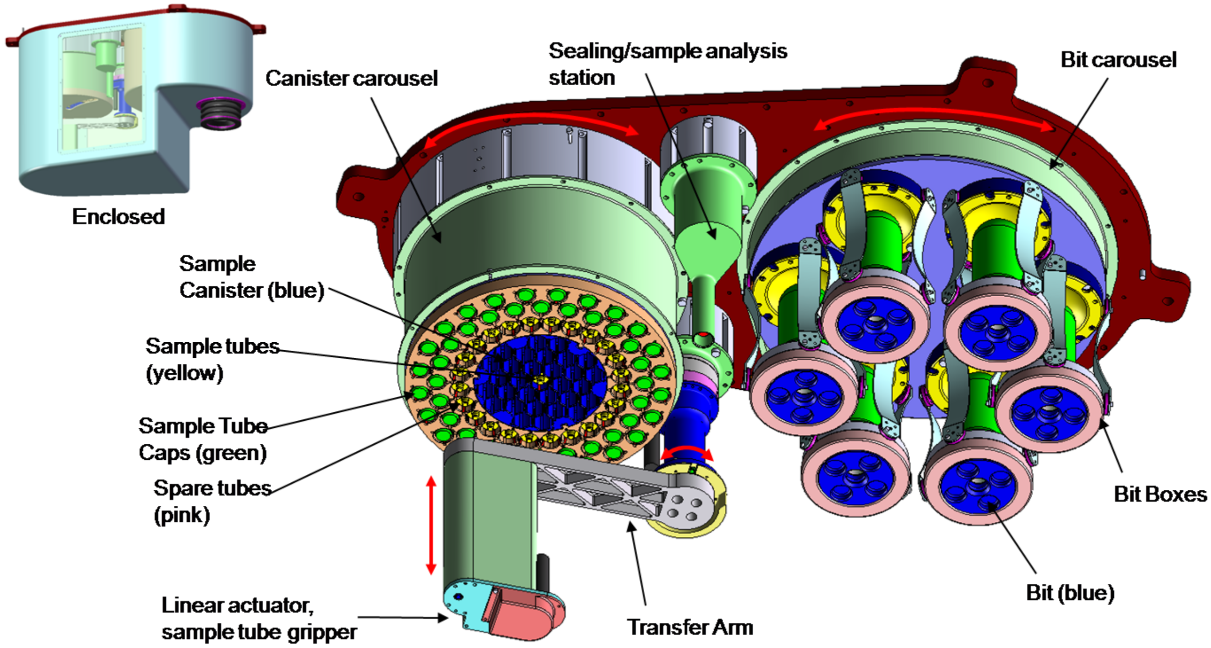

Figure 3. The Sample Handling Encapsulation and Containment (SHEC) system

tection perspective as it acquires the sample core directly into a sterile sample tube, avoiding many potential contamination pathways. This architecture is also robust to broken or pulverized core samples, as the handling system interfaces only to the sample tube and does directly manipulate the sample itself.

A conceptual design of the SHEC system is shown in Figure 3. The SHEC system provides a potentially usefully design from the perspective of round trip and cross contamination: the SHEC system contains several compartment in the design, shown in Figure 4 which block direct particle transport to many critical components. During system design, internal covers were placed to minimize internal transfer of cuttings, fines and dust present on bits after coring. These covers will also inherently impede the transport of VEMs which may enter the system. The SHEC is completely contained in a single outer enclosure. There is only one hole in this enclosure which coring bits enter and exit through. In the current SHEC design this single entry port on the cover will be covered by a door or bellow seal. This is important as when this door is closed, it effectively decouples contamination of the external system (rover, arm, etc.) from the internal SHEC components.

IMSAH components

For the purposes of analyzing the removal and transport of VEMs in the IMSAH system, the entire system is broken down into a set of components C. This component set is a compromise between enumerating every component part, including bolts, and considering only the most critical components, such as the sample tube and the sample core. A list of considered IMSAH system components is given in Figure 5. This component list groups subcomponents into larger functional groupings for convenience. Figure 5 also groups the components by their primary location, either outside or inside the SHEC, and by their criticality. For the IMSAH analysis example given in the paper, a level of cleanliness for each component was assumed. For instance, the SHEC system internals were assumed to be sterilized before launch, and kept sterile by doors and bio-barriers until the first sample and handling sequence. Other system components such as the rover body were assumed to be 'dirty', and were given a initial contamination level of 300 VEMs$/m^2$ (see Section 4 for details and assumptions on initial contamination).

IMSAH sampling sequence

The IMSAH sampling sequence, and scope of this paper begins with the rover situated in front of the sample area. We do not consider the rover drives and prescience as part of this study, although these could be added in a straightforward way.

The basic set of steps that the IMSAH system concept executes during a normal sample acquisition and handling cycle are as follows:

1. The Rover would be in a stowed configuration in front of the sample site.
2. The SHEC system inner transfer arm would pick up a sample tube (ST)
3. The SHEC system would insert the sample tube into the appropriate core bit assembly (CBA).
4. The CBA would be picked up from the SHEC by the sample acquisition tool (SAT).
5. The Tool Deployment Device (TDD) would move the SAT

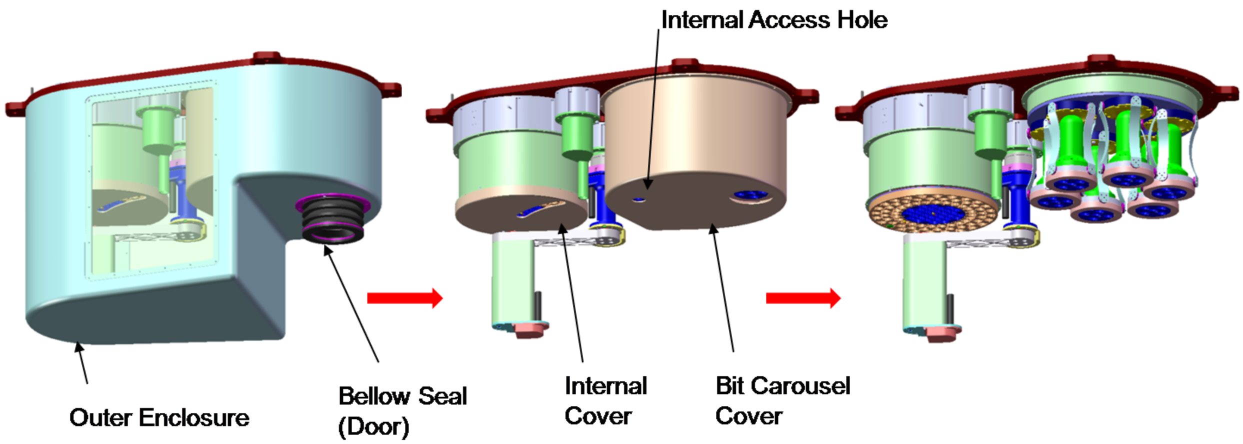

Figure 4. External and internal compartments and barriers of the SHEC system

	Component	Surface Area m2	Cleaning VEMS/m2
External	Rover Body (RB)	10	300
	Tool Deployment Device (TDD)	0.5	300
	Sample Acquisition Tool (SAT)	0.1	300
	SHEC Door (Door)	0.002827433	300
SHEC Internal	Inside Bit Box (IBB)	0.05	0
	Compartment 1 (C1)	0.5	0
	Internal Access Hole 1 (IH1)	0.000314	0
	Compartment 2 (C2)	1	0
	Transfer Arm (TF)	0.001	0
	Verification Dock (VS)	0.001	0
	Bit Assembly (CBA)	0.0021	0
	Sample Tube Cap (STC)	7.8e-05	0
	Sample Tube (ST)	7.8e-05	0
	Sample Area (Core)	7.8e-05	0

Figure 5. Component Parts: A list of relevant component parts grouped by location and criticality. The components in red: Sample Tube Cap (STC), the Sample Tube (ST) and Sample Area (Core) could all potentially be brought back to earth, and the calculation of VEMs on these components is required. An assumed level of initial cleanliness for each components is also listed.

from the SHEC to the sample rock.
6. The coring process: the CBA is preloaded against the rock sample site, and the SAT is turned on. After coring the CBA is removed from the sample hole.
7. The TDD would bring the SAT back to the SHEC.
8. The SAT would transfer the CBA (with the core sample and sample tube) into the SHEC.
9. The sample tube (and core) would be removed from the CBA.
10. The sample tube would be brought to the verification dock.
11. The sample tube would be capped.
12. The sample tube would be stored in the canister.

	Sequence	Dominant Particle Release Mechanism
S1	Stowed	Wind
S2	*SHEC Arm Move from Stowed to Canister*	
	SHEC Sample Tube Pick Up	Contact
	SHEC Arm Move from Canister to Bit Carousel	
S3	SHEC Sample Tube Insertion into Bit Assembly	Contact
	SHEC Bit carousel Rotate	
S4	TDD Unstow + Move to SHEC	
	SHEC door open	
	TDD Dock SAT with SHEC	
	SAT Bit Pickup	
	SHEC Bit Released	
	TDD undock SAT from SHEC	
	SHEC door close	
S5	TDD move SAT to rock	Wind
S6	SAT Coring Operation	Vibration
S7	TDD move SAT to SHEC	Wind
S8	SHEC door open	
	TDD Dock SAT with SHEC	Contact
	SHEC Bit Pickup	Contact
	SAT Bit Release	Contact
	TDD undock SAT from SHEC	
	SHEC door close	
	TDD stow	
S9	SHEC Bit carousel Rotate	
	SHEC Remove Sample Tube from Bit	Contact
S10	SHEC Arm Move from Bit Carousel to Verification	
	SHEC verify sample	Contact
S11	SHEC Arm Move from Verification to Cap	
	SHEC Pick Up Cap	Contact
	SHEC Arm Move from Cap to Cap station	
	SHEC Cap Sample Tube	
S12	SHEC Arm Move Cap Station to Canister	
	SHEC Insert Sealed Sample Tube into Canister	
	SHEC Arm Move to Stowed	

Figure 6. IMSAH concept sequence list: A list of the 12 steps that would be executed by the system in a normal sample acquisition and handling sequence. A corresponding set of interactions of relevant components is shown for each step S_i. A summary of the critical removal mechanisms (Section 5) is also shown for each step.

These 12 steps are further broken down by each component interaction in Figure 6. Illustrations of various IMSAH sampling steps are shown in Figure 7.

3. MoVEMenT Analysis Framework

The MoVEMenT framework, which stands for Markovian VEM Transport, has been created specifically to provide a complete description of all contamination pathways in a sample and handling (SAH) system, while making PRA analysis tractable by breaking the analysis into small discrete steps.

MoVEMenT decomposes the sample and handling (SAH) process into a set of discrete steps or operations, and also breaks the physical SAH system into a set of relevant components. This requires two inputs from the user: a complete description of all steps in the SAH process and a complete list of relevant components (or component groups) of the SAH system (see Section 2).

MoVEMenT requires two definitions from the user: a list of the n relevant components $C = \{C_i\}_{i=1}^n$ of the SAH system, and a description of each step, S_k , of the SAH process. For example, the IMSAH system (Sec. 2) has $n = 14$ relevant component groups, and 10 discrete steps, in the SAH process.

Significant to the MoVEMenT framework, one of the component groups of the SAH system is the sample itself. For IMSAH, component C_{14} = sample area. The goal of MoVEMenT is then to estimate the expected number of VEMS on each component after each discrete step S_k of the SAH process. Let:

$$E_k\left(V_i\right) = E\left[number\ of\ VEMs\ on\ C_i\ after\ step\ S_k\right] \tag{1}$$

For example, after 10 steps of the IMSAH process, $E_{10}\left[V_{14}\right]$ is the expected number of VEMS on the core sample. With a well designed and cleaned SAH system, the expected number of VEMS on the sample area should always be significantly less than one, i.e., $E_k\left[V_{14}\right] << 1$. In this case, the expectation can then be interpreted as the probability that the sample (C_{14}) has been contaminated with at least one VEM. This interpretation is slightly conservative, but becomes exact as $E_k\left[V_{14}\right] \to 0$.

MoVEMenT uses a temporal Markovian decomposition for estimating $E_k\left[V_i\right]$. Simply, it is assumed that the number of VEMS on any component C_i at the end of SAH step S_k, only depends on the distribution of VEMS over the components set C at the end of step S_{k-1}.

The movement of VEMS between the components in set C during step S_k components of the SAH system components at each SAH step is assumed to be modeled by two independent phenomena. First for a VEM to move from component C_i to C_j a VEM carrying particle needs to be released from component C_i. The probability of a VEM being released from component C_i during step S_k is:

$$P_k\left(R_i\right) = P\left(\begin{array}{c} a\ VEM\ carrying\ particle\ is \\ released\ from\ component\ C_i \\ during\ S_k \end{array}\right) \tag{2}$$

Note that this document will use the "number of VEMS" and the "number of particles carrying VEMS" interchangeably. This is due to the assumption that the expected number of VEMS on any given particle within the size-range of interest (0-300 μm) is << 1. For example even for a 300 μm particle, there is only a 0.0053 chance it contains a VEM (Section 4). The probability of VEM release from a given component will need to be modeled in an appropriate way. Section 5 discusses and models different release mechanisms including vibration, wind, and tribioletric charging.

After a VEM carrying particle has been released from component C_i, the particle is potentially able to contaminate component C_j. The particle transport model is encapsulated in the probability:

$$P_k\left(T_{ij}\right) = P\left(\begin{array}{c} a\ released\ particle\ from\ C_i\ is \\ transported\ to\ C_j\ during\ S_k \end{array}\right) \tag{3}$$

It is assumed that if a particle reaches a new component C_j, that it will adhere to that component with probability 1. This assumption could be relaxed in the future if required.

The estimated number of VEMS on any component can now be written in terms of the expected distribution of VEMS on all components at the end of the previous sample and handling step S_{k-1}

$$\begin{aligned} E_k\left[V_j\right] = \quad & \left(1 - P_k(R_j)\right) E_{k-1}\left[V_j\right] + \\ & \textstyle\sum_{i=1}^N P_k(T_{ij}) P_k(R_i) E_{k-1}\left[V_i\right] \end{aligned} \tag{4}$$

For convenience, this can be written as a standard Markov chain:

$$E_k[V] = A_k E_{k-1}\left[V\right] \quad , \tag{5}$$

where $V = [V_1, ..., V_N]^T$, and:

$$A_k = [(A_k)_{ij}] = \left\{ \begin{array}{ll} 1 - P_k(R_i) + P_k(T_{ii}) P_k(R_i) & if\ i = j \\ P(T_{ij}) P_k(R_i) & else \end{array} \right. \tag{6}$$

Writing the expectation of the contamination of each component as a Markov chain (5) has several advantages. First, it allows for verification that all of the component probabilities $P_k(R_i)$ and $P_k(T_{ij})$ are self consistent. In short, the rows of the matrix $[T_{ij}]$ and the matrix A_k should sum to 1. Checking this for self consistency will eliminate many overlooked probabilities and typographical errors. Furthermore, as the expectation at several steps S_k of the sampling process are executed, it should be verified that $\sum(E_k[V]) = \sum(E_{k'}[V])$, $\forall\ k, k' \in 1, ..., K$, that is the total expected number of VEMs remains constant.

Also, many useful properties of Markov chains can be utilized in the final analysis of the sample contamination pathways.

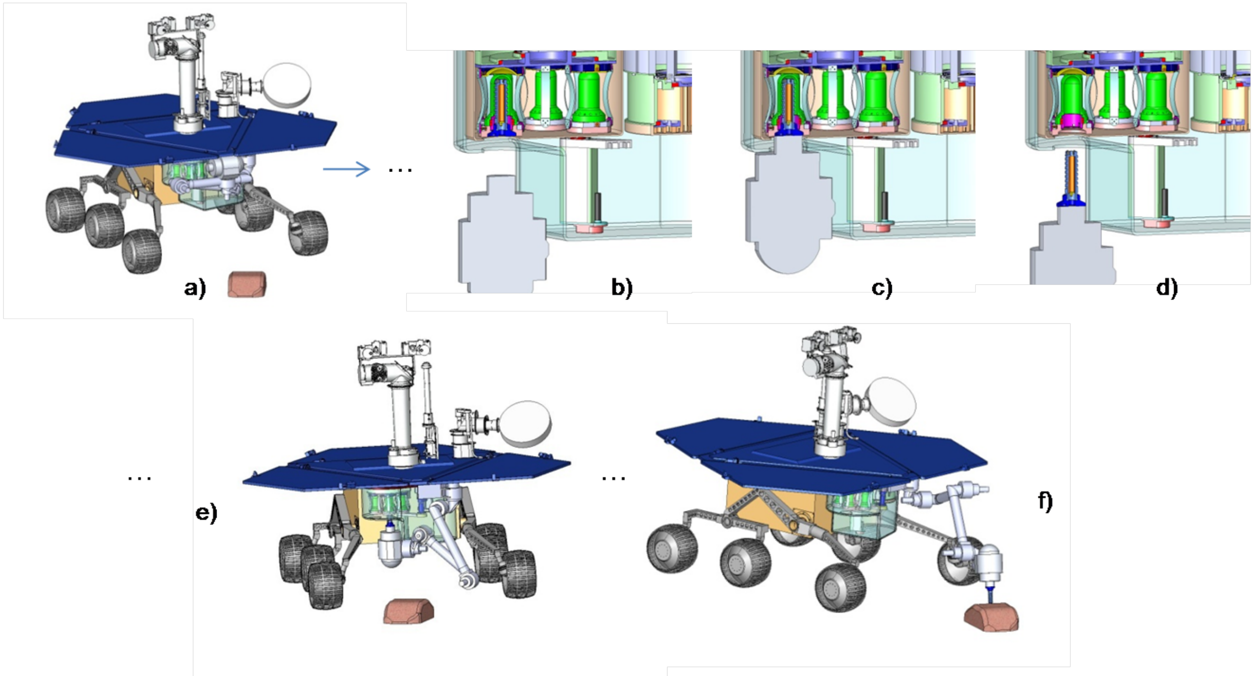

Figure 7. Selected IMSAH concept sequence steps: a) The rover is in state S_1, stationary in front of the rock. b)-d) shows part of S_2, where the SAT picks up the core bit. S_5 is shown from e)-f) where the SAT to the rock. f)- Start of the coring

For instance, the composition of multiple transition kernels A_k will give the contribution of contaminates in the sample from each component source. For example, in the IMSAH concept system, after 10 sampling steps, the columns of the composition:

$$A' = A_{10}A_9...A_2A_1 \quad (7)$$

will give the expected destinations (or source) of a contaminate from (to) each component.

The remaining work in this document will approach estimating the various probabilities $P_k(R_i)$ and $P_k(T_{ij})$ associate with each sampling and handling step S_k. While this MoVEMenT framework does not make this further analysis any easier, it provides a method to analyze all of these problems on their own and then integrate them in a reliable way. If it is difficult to ascertain some of the probabilities $P_k(R_i)$ and $P_k(T_{ij})$, then the sensitivity of the final expectations to these probabilities can be analyzed in a straightforward way by considering intuitive metrics like analyzing the change in the columns of A'.

4. Initial Contamination Levels

The initial contamination level for IMSAH system components were assumed to either be dirty at a 300 VEMs/m^2 level, or sterile. The 300 VEMs/m^2 level is assumed as an approximation for fallout in a class 100K clean room. For this contamination level, a distribution of corresponding particle sizes and an estimate of the number of VEMs per particle is defined from [2] and [3].

In [3] the particle size distribution is based on data obtained with a Pentagon sampling device for particles smaller than 10 μm. The particle size distribution was then extended by scaling the MIL-STD-1446 distribution to fit the spore data for the spore-per-particle model derived in [2].

The final particle size distribution and the number of VEMS per particle are given in Figure 8. This 300 VEMs/m^2 level of contamination will be used for all non-sterilized parts in the analysis.

	Particle Size Range (µm)																				
	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-200	200-300	TOTAL
particles/m2	7.6E+6	4.3E+6	2.4E+6	1.4E+6	3.8E+5	2.8E+5	2.1E+5	1.6E+5	1.2E+5	4.5E+5	8.7E+4	2.6E+4	1.0E+4	4.7E+3	2.4E+3	1.3E+3	7.5E+2	4.6E+2	9.2E+2	5.2E+1	
spores/ particle	9.7E-8	1.4E-6	1.2E-5	2.0E-5	2.7E-5	3.5E-5	4.3E-5	5.1E-5	5.8E-5	2.5E-4	4.5E-4	6.4E-4	8.3E-4	1.0E-3	1.2E-3	1.4E-3	1.6E-3	1.8E-3	3.7E-3	5.7E-3	
spores/m2	7.4E-1	5.8E+0	2.9E+1	2.7E+1	1.1E+1	9.9E+0	9.0E+0	8.0E+0	7.2E+0	1.1E+2	3.9E+1	1.7E+1	8.6E+0	4.8E+0	2.9E+0	1.8E+0	1.2E+0	8.3E-1	3.4E+0	2.9E-1	**300.37**

Figure 8. Assumed particle size distribution and VEMs per particle corresponding to a 300 VEMs$/m^2$ contamination level.

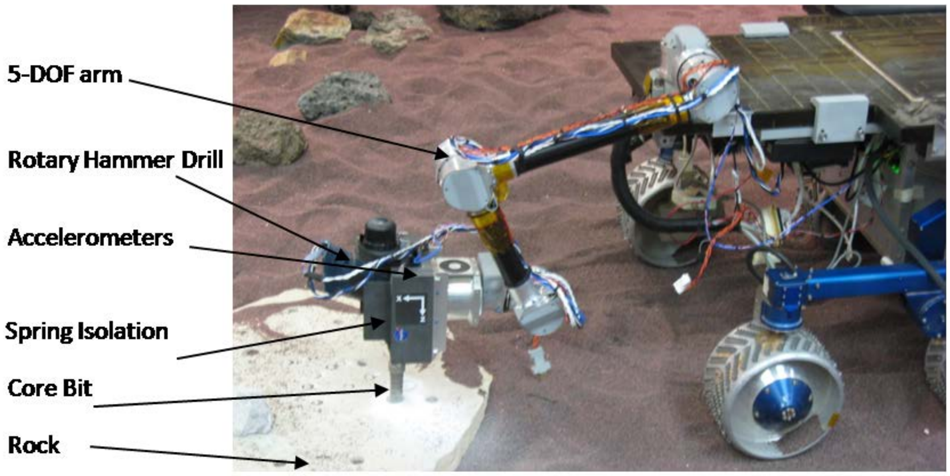

Figure 9. Drilling from a FIDO rover: A rotary percussive coring tool is mounted on a 5-DOF robotic arm and is used to acquire core samples.

5. Wind Release and Transport Models

There has been considerable previous work on particle transport due to Martian winds. The analysis in this paper considers two possible cases of wind that must be considered. First, normal surface winds, assumed to be approximately parallel to the surface of Mars, and second abnormal wind events such as dust devils.

Winds on Mars

Significant work has been done on particle removal due to wind in Martian conditions [2], [4]. This paper assumes removal models due to wind from [2], which coincide with previous 'lower bound' results that steady winds of less then 15 m/s are unlikely to remove any $1-300\mu m$ particles from their adhering surface [4].

We assume that no particles (and no VEMs) are removed from any part of the rover due to nominal surface wind conditions. This is based on a survey of several direct and indirect measurements of winds on the Martian surface, none of which estimate nominal winds of $15m/s$ occurring over a large sample set of places on the Martian surface. Specifically, the limited data from Pathfinder [5] recorded winds up to 10 m/s. Data from the Phoenix landing site [6] record data up to 12m/s. All of these Martian wind data products are also available on JPL's public Planetary Data System. Even estimated data for winds above landing sites [7] takes a maximum over many different sample sites of $14 + -5m/s$.

Unfortunately, taking simple steady state wind values and predicting particle removal may be an inadequate strategy [4]. For instance, the MER rovers demonstrated that particles of a few microns in size could be detached by wind events, as illustrated by the cleaning of the solar panels. Other factors such as turbulent wind gusts, and dust devils may need to be taken into account. While no claim is made that steady state wind on Mars will not exceed a relevant value ($> 15m/s$), any engineering approach to make a stochastic wind model based on recorded data will not remove particles from the rover surface. Future work will incorporate better wind removal and transport models that utilize the product of wind tunnel and computer modeling [4].

Dust Devils

The analysis undertaken in this paper makes an attempt to incorporate the possibility of a dust devil removing and redistribution particles on the IMSAH system components. A basic approach is taken in modeling the removal of particles by dust devils: all particles are removed. However, the probability that a dust devil intersects the rover is given as small expected occurrence of $1/1000$ per sol. This estimate will be updated with a future literature survey and research.

The model for the transport (or redistribution of particles) due to the dust devil is created by considering the areas of all component involved. That is, we assume that all exposed surfaces get an even distribution of particles removed form the surface

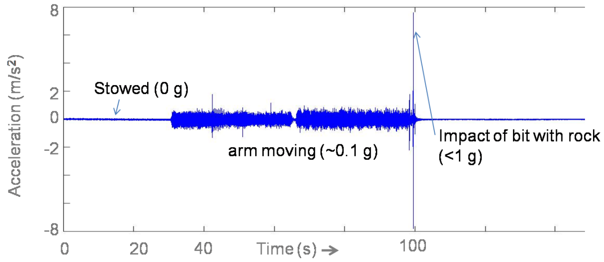

Figure 10. Example of vibrations during arm deployment.

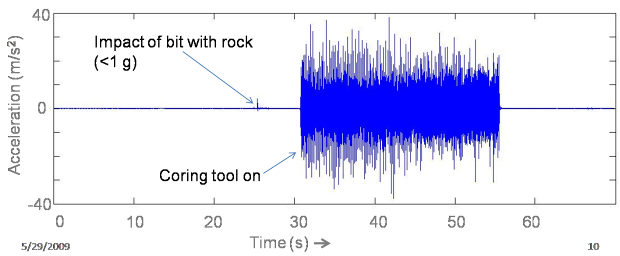

Figure 11. Example of vibrations during coring. Accelerations were measured on the SAT mounted on the TDD turret. These accelerations are highly damped by the arm, resulting in limited propagation to the rover body.

of the rover, including the ground (which we take to be a 5 m diameter area around the rover). Thus, independent of orientation, it is assumed the number of particles on each component is proportional to its surface area. While these release and transport models involved with dust devils are unlikely to represent the realities of Mars, no other analysis was available for incorporation into the PRA.

6. Vibration Release and Transport Models

The analysis of particle removal due to vibration consisted of two parts. First, a series of acceleration profiles was measured during various rover actions. Second, these accelerations were combined with a general particle release model from [2] to estimate the probability of particle release.

Vibration Measurements

To estimate the vibrations relevant to particle release during the IMSAH process, accelerometers were attached to various parts of representative experimental IMSAH testbed [8]. This testbed, shown in Figure 9, consists of a rotary percussive tool attached to the end of a 5-DOF robotic arm mounted on a low-mass FIDO rover. Accelerations were monitored during various stages of the IMSAH process, in particular S_5, the extension of the arm to the rock (Figure 10) and S_6, the coring process (Figure 11).

Particle Release Models

To estimate the removal fraction of particles for a given acceleration, the release model from [2] was used. This release

	Max. Acceleration (m/s²)	VEMs Removed /m²
	1.E-01	2.14E-29
SHEC movement	5.E-01	4.31E-18
Arm Movement	1.E+00	3.83E-14
	5.E+00	4.30E-07
Initial Drill bit impact with rock	8.E+00	9.29E-06
	1.E+01	5.88E-05
	2.E+01	5.93E-04
Drilling	5.E+01	5.67E-02

Figure 12. Expected number of VEMs released due to acceleration for a $1m^2$ surface area with 300 VEMs/m^2 with particle size distribution from Fig. 8

model gives the release fraction for a given particle size and applied force, and is based on experimental results:

$$f = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\log k} e^{-\frac{t^2}{2}} dt \ , \quad (8)$$

with

$$\log k = (\log(F/d) - \log(k_0))/\sigma \ , \quad (9)$$

where f is the removal fraction, F is the applied force (N), d is the particle size (m), and k_0 and σ are adhesion force parameters. Following [2], we use the most conservative estimate, corresponding to minimum credible adhesion, and set $\log k_0 = -2.44$, and $\sigma = 0.265$.

To convert the measured accelerations into a force, a particle density of $2gm/cm^3$ was assumed. Further assuming that the particles are spherical gives the mass of each particle. Now the Newton's second law $F = ma$ can be used to substitute force for acceleration in equation (9).

For reference, the expected number of VEMs removed from a $1m^2$ surface area with 300 VEMs m^2, with particle size distribution as in Figure 8, for a given acceleration is shown in Figure 12. Given the area of the TDD and SAT is approximated at less then $1m^2$, vibration is typically not a significant cause of VEM release. The next section will address the coring process in more detail, and also describe how VEM release from vibration during coring does not pose significant contamination risk.

7. Coring Release and Transport

Coring inherently presents a cleaner method of sampling then drilling or digging. The sample core would be effectively covered by the coring bit during the coring process, preventing any direct transport path into the sample. Particles on the outside of the coring bit would be removed and transported with removed rock fines, away from the sample, illustrated in Figure 13. In the IMSAH system concept, the SAT does not turn on until the core bit is preloaded against the target site [8]. This implies that any particles that are released due to coring vibration (Figure 12), could not reach the critical sam-

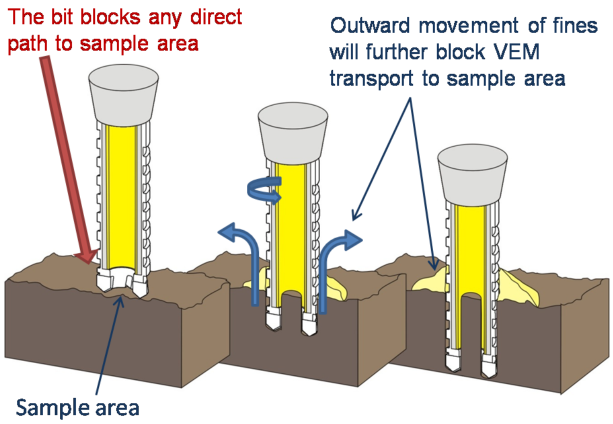

Figure 13. The IMSAH coring process would eliminate the transport of a VEM released by coring vibration from entering the sample chain. The coring tool would not be turned on until after it is preloaded against the target rock, removing a direct transport path to the target sample area, or the sample tube inside the coring bit.

ple core or sample tube components, and would with a high probability land on the ground.

Particle Transport from Core Bit Rotation

The transport of particles from the rotation of the core bit during the coring process was considered. The IMSAH core bit diameter would likely be less than 21mm. The assumed maximum rotation speed likely to be used while coring is 350 rpm [8]. This implies that the tangential bit velocity, and hence released particles, could reach velocities of 23.6 m/s. Small particles moving at these speeds would likely have their velocity reduced to the ambient wind velocity within cm's of leaving the bit. Because of this, there is no significant chance that particles removed from the bit would return to system components other than the ground while coring.

8. Electrostatic Release Models

Current Mars Science Laboratory (MSL) testing experience indicates that particle movement (rubbing) can cause differential charge between hardware and samples (Triboelectric charging). This causes either increased or decreased adhesion of particles.

While Tribolectric charging is a problem for sample acquisition (tracking adhesion of Martian particles), it is not relevant for removal of VEMs, which are contained on Earth based particles. It is assumed that the earth based particles have been on the rover for a long duration, and are therefore not differentially charged to the rover. Furthermore, for the particles to become triboelectrically charged, the particle would have to move relative to the rover surface, implying removal. Particle charging from solar effects have not yet been considered.

9. Mechanical Contact Release and Transport Models

The modeling of particle release and transport due to the mechanical interaction and contact of IMSAH system component parts is not approached in a realistic manner. Due to the lack of experimentally verified results involved in small (1-300 μm) particle, and unknown IMSAH system parameters such as surface roughness and fit tolerances, a simple release and transport model was assumed: All VEMs on components that contact are transfered from the least critical component to the most critical component. We defined the three most important components to be the sample core, the sample tube, and the sample cap.

Unfortunately, the chosen release and transport model will give completely unrealistic results that greatly overestimate the chance a VEM would enter the sample chain. Future work will focus on experiments to quantify particle transport due to contact, and investigate associated modeling tools.

10. Results

The MoVEMenT framework was applied to a single sample sequence of the IMSAH system concept (Figure 14). The results of this analysis clearly indicate a primary transport pathway: the release of VEMs from the SHEC door due to mechanical contact when the SAT picks up the CBA. Unfortunately, this primary pathway illustrated in Figure 14 is grossly overstated due to the simple contact model described in Section 9.

Instead of changing the model used for mechanical contact, the current analysis is modified by investigating changes in the IMSAH system. One of the goals in creating the MoVEMenT framework was the ability to affect design of sample and handling systems at early stages of development. Specifically the IMSAH design now is changed by placing a bio-barrier over the entrance to the SHEC, and removing the SHEC door to reduce complexity. Here it is now assumed that the bio-barrier would be a one-time-deployable cover that would be ejected after landing and long before any coring process.

This change in the IMSAH design does two things: First, the initial contamination of the door mechanism would be removed. Second the removal of the SHEC door would now expose the inside of bit box (IBB) to the Martian environment during normal operations. It is assumed that the deployment of the bio-barrier would be designed such that no additional VEMS come off the bio-barrier and land on the rover or other modeled components. The results of this IMSAH design change is presented in Figure 15. The modified IMSAH design, augmented with a bio-barrier shows a greatly reduced contamination probability, even with the SHEC door removed.

Group	Step:	Start	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
	Step Name	**Start (Initial Condition)**	Stowed	Tube Pick Up	Insert Tube into Bit	CBA Pickup by SAT	TDD moves to Rock	Coring Operation	TDD moves to SHEC	Transfer CBA to SHEC	Remove ST from CBA	Verify Sample	Cap Sample Tube	Store Sample Tube
	Component	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]
External	Rover Body (RB)	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3
External	Tool Deployment Device (TDD)	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2
External	Sample Acquisition Tool (SAT)	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1
External	SHEC Door (Door)	8.5E-1	8.5E-1	8.5E-1	8.5E-1	0.0E+0	2.9E-7	2.9E-7	5.7E-7	5.7E-7	5.7E-7	5.7E-7	5.7E-7	5.7E-7
External	Ground	0.0E+0	3.2E+0	3.2E+0	3.2E+0	3.2E+0	3.2E+0	3.4E+0	3.4E+0	3.4E+0	3.4E+0	3.4E+0	3.4E+0	3.4E+0
SHEC Internal	Inside Bit Box (IBB)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SHEC Internal	Compartment 1 (C1)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SHEC Internal	Internal Acess Hole 1 (IH1)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SHEC Internal	Compartment 2 (C2)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SHEC Internal	Inner Transfer Arm (TA)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
SHEC Internal	Verification Dock (VA)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Critical	Bit Assembly (CBA)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	2.2E-7	2.2E-8	2.4E-7	3.9E-7	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Critical	**Sample Tube Cap (STC)**	**0.0E+0**	**0.0E+0**	**0.0E+0**	**0.0E+0**	**0.0E+0**	**0.0E+0**	**0.0E+0**	0.0E+0	0.0E+0	**0.0E+0**	**0.0E+0**	**0.0E+0**	**0.0E+0**
Critical	**Sample Tube (ST)**	**0.0E+0**	**0.0E+0**	**0.0E+0**	**0.0E+0**	**8.5E-1**	8.5E-1	8.5E-1	8.5E-1	8.5E-1	**8.5E-1**	8.5E-1	8.5E-1	8.5E-1
Critical	**Sample Area (Core)**	**0.0E+0**	**8.0E-7**	**8.0E-7**	**8.0E-7**	**8.0E-7**	**8.0E-7**	**8.0E-7**	**8.1E-7**	**8.8E-7**	**8.8E-7**	**8.8E-7**	**8.8E-7**	**8.8E-7**
	total # VEMS	3184.8347												3184.8347

Group	Component	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
		E[VEMS Released]	E[VEMS Released]	E[VEMS Released]	E[VEMS Released]	E[VEMS Released]	E[VEMS Released]	E[VEMS Released]	E[VEMS Released]	E[VEMS Released]	E[VEMS Released]	E[VEMS Released]	E[VEMS Released]
External	Rover Body (RB)	3.003	0	0	0	0.030	0	0.0309	0	0	0	0	0
External	Tool Deployment Device (TDD)	0.1501	0	0	0	0.00150	0.02829	0.00150	0	0	0	0	0
External	Sample Acquisition Tool (SAT)	0.0300	0	0	0	0.0003	0.17089	0.00029	0.2983	0	0	0	0
External	SHEC Door (Door)	0	0	0	0.8491	0	0	0	2.86E-7	0	0	0	0
External	Ground	0	0	0	0	0	0	0	0	0	0	0	0
SHEC Internal	Inside Bit Box (IBB)	0	0	0	0	0	0	0	0	0	0	0	0
SHEC Internal	Compartment 1 (C1)	0	0	0	0	0	0	0	0	0	0	0	0
SHEC Internal	Internal Acess Hole 1 (IH1)	0	0	0	0	0	0	0	0	0	0	0	0
SHEC Internal	Compartment 2 (C2)	0	0	0	0	0	0	0	0	0	0	0	0
SHEC Internal	Inner Transfer Arm (TA)	0	0	0	0	0	0	0	0	0	0	0	0
SHEC Internal	Verification Dock (VD)	0	0	0	0	0	0	0	0	0	0	0	0
Critical	Bit Assembly (CBA)	0	0	0	0	0	2.2E-7	0	2.22E-8	3.8E-7	0	0	0
Critical	**Sample Tube Cap (STC)**	0	0	0	0	0	0	0	0	0	0	0	0
Critical	**Sample Tube (ST)**	0	0	0	0	0	0	0	0	0	0	0	0
Critical	**Sample Area (Core)**	0	0	0	0	0	0	0	0	0	0	0	0

Figure 14. Inital study of the probability that at VEM enters the sample and handling chain. Both the transport summary (top) showing the expected number of VEMs on each component, and the Release summary, of the number of VEMs released from each component are shown for a sequence of 12 IMSAH steps. Note that the primary contamination pathways are the inital (300 VEM$/m^2$) contamination of the SHEC door being transfered during mechanical contact. The release mechanisms are color-coded: ORANGE represents mechanical contact, RED represents vibration release, and BLUE represents wind (dust devil) release.

11. Conclusions

MoVEMenT, or Markovian VEM Transport, is new mathematical framework and software implementation developed for evaluating the probability of a Viable Earth Microorganism (VEM) contaminating a sample during sample acquisition and handling process. MoVEMent was applied to estimting the probability of a VEM entering the sample chain for the Integrated Mars Sample Acquisition and Handling system concept. Results show that a potential cause of contamination could occur due to contact between the core bit and the sample and handling system door, which was assumed to be dirty to a 300 VEMs$/m^2$ level. Limited models for particle release and transport caused mechanical contact give unrealistically high probability levels of contamination. The MoVEMent framework allowed identification of this contamination pathway, which then allowed a simple logical redesign of the IMSAH system concept. A bio-barrier was placed over the SHEC doorway, reducing the probability that the door was contaminated and hence reducing the entire system's probability of allowing a contaminate to enter the sample chain. The MoVEMenT framework was then rerun, and demonstrated a significantly decreased probability of contamination.

Acknowledgments

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

	Step:		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
	Step Name	Start (Initial Condition)	Stowed	Tube Pick Up	Insert Tube into Bit	CBA Pickup by SAT	TDD moves to Rock	Coring Operation	TDD moves to SHEC	Transfer CBA to SHEC	Remove ST from CBA	Verify Sample	Cap Sample Tube	Store Sample Tube
	Component	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]	E[# VEMS]
External	Rover Body (RB)	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3	3.0E+3
	Tool Deployment Device (TDD)	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2	1.5E+2
	Sample Acquisition Tool (SAT)	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1	3.0E+1
	Ground	0.0E+0	3.2E+0	3.2E+0	3.2E+0	3.2E+0	3.2E+0	3.4E+0	3.4E+0	3.4E+0	3.4E+0	3.4E+0	3.4E+0	3.4E+0
SHEC Internal	Inside Bit Box (IBB)	0.0E+0	2.9E-5	2.9E-5	2.9E-5	0.0E+0	2.9E-7	2.9E-7	5.8E-7	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
	Compartment 1 (C1)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
	Internal Acess Hole 1 (IH1)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
	Compartment 2 (C2)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
	Inner Transfer Arm (TA)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
	Verification Dock (VA)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Critical	Bit Assembly (CBA)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	2.2E-7	2.2E-8	2.4E-7	5.3E-7	0.0E+0	0.0E+0	0.0E+0	0.0E+0
	Sample Tube Cap (STC)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
	Sample Tube (ST)	0.0E+0	0.0E+0	0.0E+0	0.0E+0	2.9E-5	2.9E-5	2.9E-5	2.9E-5	2.9E-5	2.9E-5	2.9E-5	2.9E-5	2.9E-5
	Sample Area (Core)	0.0E+0	8.0E-7	8.0E-7	8.0E-7	8.0E-7	8.0E-7	8.0E-7	8.1E-7	8.1E-7	8.1E-7	8.1E-7	8.1E-7	8.1E-7

Figure 15. Modified study of VEM contamination during sample and handling (SAH). A one-time deployable bio-barrier was added to the system (not shown) which is discarded before the SAH process. The SHEC door has been removed, allowing open air access to the inside of the bit-box (IBB). In this analysis, contamination of the bit box due to dust devil events (blue) are the initiating cause of sample contamination, brought on through CBA contact (orange) with the bit-box. Note that the dust devil model used does not incorporate the geometry of the bit-box, which is recessed into the SHEC subsystem, and may be sheltered from even extreme wind events such as dust devils.

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Biography

Nicolas Hudson, PhD is a member of the Mobility and Manipulation group at Jet Propulsion Laboratory. He received his Masters in Mechanical Engineering and Ph.D. from California Institute of Technology in 2004 and 2008, respectively, and a Bachelor in Engineering degree from the University of Canterbury, Christchurch, New Zealand, in 2002. He received the Sir William Pickering Fellowship at the California Institute of Technology and Ian McMillan Prize and C S McCully Scholarship at the University of Canterbury. His primary area of research at JPL is robotics autonomy for sample acquisition.

Dr. Ying Lin is currently a Planetary Instrument Development Manager at JPL Planetary Science Instrument Development Office. She manages JPL's planetary science instrument research tasks funded by NASA. She is also a senior member technical staff at JPL's biotechnology and planetary protection group. She has extensive research experiences in biotechnology and instrument development. She is the PI and Co-I of several proposals funded by JPL and NASA on planetary protection and biosensor development tasks. She has been the technical lead of planetary protection technology development for NASA Mars Technology Program since 2004.

JackB. Barengoltz is a former principal member of the technical staff in the Biotechnology and Planetary Protection Group of the Mechanical Systems Division at the Jet Propulsion Laboratory, California Institute of Technology. He retired in January 2006. Dr. Barengoltz received a BS in physics from Carnegie Institute of Technology (now Carnegie Mellon University) in 1965 and an MS and PhD in physics from the University of Illinois in 1967 and 1970, respectively. During his career at JPL, Dr. Barengoltz conducted research and performed analysis concerning contamination for space and energy programs. His specialties in the field are particulate, molecular and microbiological contamination as it applies to spaceflight systems. His principal contributions for most of his career were in planetary protection (PP), both in research and in the PP implementation of many spaceflight projects. He has received NASA Exceptional Service medals for contamination control and for planetary protection. Currently, Dr. Barengoltz consults with JPL, NASA and the European Space Agency in PP matters. Dr. Barengoltz is a member of the American Physical Society and the American Institute of Aeronautics and Astronautics, and a senior member of the Institute of Environmental Sciences and Technology.