

**TESTING OF MAGNETS FOR THE MARS EXPLORATION ROVER MISSIONS.** J. Jensen<sup>1</sup>, P. Bertelsen<sup>2</sup>, F. Folkmann<sup>1</sup>, K. Kinch<sup>1</sup>, W. Goetz<sup>2</sup>, H. P. Gunnlaugsson<sup>1</sup>, R. Jakobsen<sup>2</sup>, J. M. Knudsen<sup>1</sup>, M. B. Madsen<sup>2</sup>, J. P. Merrison<sup>1</sup>, P. Nørnberg<sup>3</sup>, C. Søgaard<sup>2</sup>, <sup>1</sup>Department of Physics and Astronomy, Aarhus University, Ny Munkegade, DK-8000 Århus C, Denmark (hpg@phys.au.dk), <sup>2</sup>Center for Planetary Science, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark, <sup>3</sup>Department of Earth Science, Aarhus University, Ny Munkegade, DK-8000 Århus C.

**Introduction:** The Viking landers and the Pathfinder lander carried instrument packages to investigate the magnetic properties of the soil and dust on Mars [1,2]. The instruments consisted of small permanent magnets that attracted and accumulated magnetic dust particles from suspension in the Martian atmosphere. From the results [3–6] we know that there is a strong magnetic component in the Martian soil and dust.

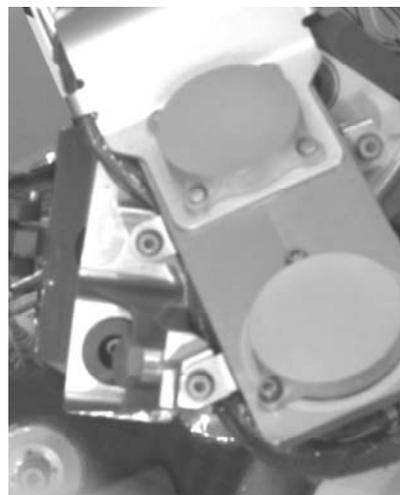
Based on both magnetic and optical properties of the dust accumulated on the magnets, the magnetic phase has tentatively been identified as maghemite,  $\gamma\text{-Fe}_2\text{O}_3$ , present as cement in or stain on silicate agglomerates [5]. However, it is not possible to exclude that the magnetic phase could be titanomagnetite ( $\text{Fe}_{3-x}\text{Ti}_x\text{O}_4$ ) or titanomaghemite ( $\gamma\text{-Fe}_{2-x}\text{Ti}_x\text{O}_3$ ) having been inherited directly from the bedrock [3,7,8]. The magnetic dust is of considerable interest as it may give important clues about the role of water in the soil forming processes on Mars [9,10]: Has the formation of the red soil on Mars taken place predominantly via oxidation of Fe(II) in aqueous solution eons ago, when Mars was warmer and wetter? Or is the soil formation an ongoing process of breakdown and oxidation of surface rocks — possibly without any appreciable role of water? In the former case, the magnetic phase in the soil/dust would not be expected to contain the element titanium, while in the latter case the magnetic phase would be expected to be an Fe–Ti oxide. Direct measurement of the Ti/Fe ratio of material accumulated by magnets on Mars could hence give insight into the soil formation processes on Mars.

NASA's Mars Exploration Rover missions (launched May/June 2003, landing in early 2004) [11] carries two magnets [12] of differing strength that will accumulate magnetic dust suspended in the Martian atmosphere for investigation with Mössbauer spectroscopy [13] and  $\alpha$ -particle X-ray fluorescence spectroscopy (APXS) [14].

In this contribution, we describe in some detail the magnets that will be used for Mössbauer spectroscopy and APXS spectroscopy, and present some preliminary results obtained in an environmental chamber that simulates the conditions on Mars.

**Magnets for the MER mission:** The Mars Exploration Rovers carry a series of permanent magnets of various strengths and dimensions. The magnets are given the following names: Filter Magnet, Capture Magnet, Sweep Magnets, and the RAT Magnets. The RAT (= Rock Abrasion Tool) is a grinding tool designed to remove weathering crust from rocks and expose fresh rock material for investigation [15]. The RAT contains built-in magnets that are designed to catch magnetic dust during grinding [12,16]. The Sweep Magnets are designed in such a way that within a certain area on the active surface, approaching magnetic particles will be deflected, and only non-magnetic particles will be allowed to settle [12].

*Capture Magnet and Filter Magnet.* The Capture and Filter Magnets are located on the front of the rovers (see Fig. 1), so that airborne dust attracted to the magnets can be studied by the Mössbauer spectrometer and the APXS spectrometer.

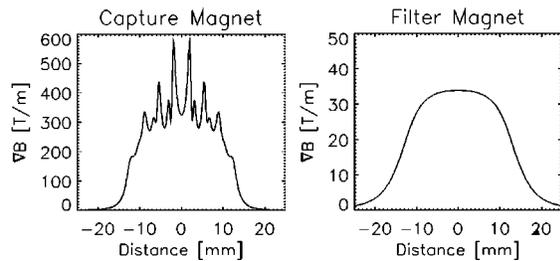


**Fig. 1: Picture of the Capture and Filter Magnets, as observed using the multispectral panoramic imager, Pancam. The Filter Magnet is in the lower right and the Capture Magnet is in the top center of the image (Credits: NASA/JPL /Cornell).**

The magnets have circular symmetry and the magnetic material used is  $\text{Sm}_2\text{Co}_{17}$  ( $\mu_0 M = 1.1$  T at room temperature) embedded in a carrying structure made of aluminum. The  $\text{Sm}_2\text{Co}_{17}$  part has a diameter of 25 mm,

while the aluminum carrying structure has a diameter of 45 mm.

The main difference between the two magnets is the surface magnetic field strength. Fig. 2 shows the variation of the magnitudes of the magnetic field gradient across the active area for the Capture and Filter magnets.



**Fig. 2: The magnitude of the magnetic field gradient at the surface of the Capture and Filter Magnets.**

For the Capture Magnet, the maximum values of  $B$  and  $|\nabla B|$  are 0.46 T and 550 T/m respectively, and for the Filter Magnet, the corresponding numbers are 0.2 T and 34 T/m.

The Filter and Capture Magnets are both equipped with sets of surface markings. The purpose of these markings is to assist in the evaluation of the thickness of the layer of dust that has accumulated on the magnets at the time of observation. Such an evaluation will be valuable in determining the optimal time for recording of an APX-spectrum and a Mössbauer spectrum of the dust on the magnets.

**Experimental:** The wind tunnel system at Århus University has been described previously [17]. Particle speed and volume number density of particles are monitored by a Laser Doppler Anemometer and dust doses are given in Sols (of exposure), assuming particle density in the atmosphere of  $1 \text{ cm}^{-3}$  on Mars. All experiments were performed at room temperature using air at 10 mbar. The magnets were tilted  $\sim 45^\circ$  relative to the vertical. X-ray fluorescence (XRF) spectra were measured (outside the wind tunnel) using a 60 mCi closed source of  $^{244}\text{Cm}$  and a  $7 \text{ mm}^2$  AMPTEK<sup>TM</sup> detector in a setup that simulates the corresponding experiment on the surface mission on Mars. As a closed source is used it does not emit  $\alpha$  particles. This limits the detection to elements with  $Z > 18$ . Mössbauer measurements were performed at room temperature using a conventional setup in transmission geometry. This differs from the setup on Mars, where the dust on the magnets will be measured in-situ in backscatter geometry. For the Mars analogue soil sample used in the present study (Salten Skov) this has minimal effect on the spectrum, and does not alter the con-

clusions that can be drawn from the experiments. Velocities and isomer shifts are given relative to the spectrum of  $\alpha\text{-Fe}$  at room temperature.

At the site called Salten Skov in Jutland, Denmark, magnetic ( $\sigma_s > 1 \text{ Am}^2/\text{kg}$ ) iron rich (Fe  $\sim 30 \text{ wt.}\%$ ) soil has been found [18,19]. X-ray diffraction and Mössbauer spectroscopy have revealed that the soil contains the magnetic iron oxides hematite ( $\alpha\text{-Fe}_2\text{O}_3$ ) and maghemite ( $\sim 30\%$  of the spectral area in Mössbauer spectrum) in mixtures with the antiferromagnetic mineral goethite ( $\alpha\text{-FeOOH}$ ). The particle size of the soil has been determined to be  $\sim 2 \mu\text{m}$  when dispersed in an ultrasonic bath. By means of transmission electron microscopy and the line broadening of the X-ray diffraction lines, it has been found that individual particles consist of smaller, nanometer sized particles of iron oxides that show superparamagnetic blocking on the timescale of Mössbauer spectroscopy.

**Results:** Most of the results presented here were obtained with a wind velocity of 2.2 m/s. After the end of the experiment (here 275 Sols), the dust was removed from the magnets and used for further investigations.

*Mass accumulations.* Table 1 summarizes the results from mass measurements.

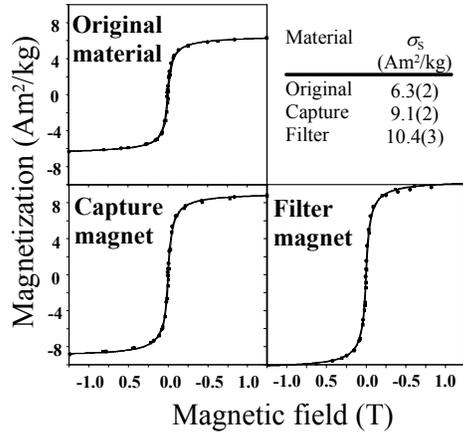
**Table 1: Results from mass measurements after exposure corresponding to 275 Sols. Included is data for 2.7 m/s for comparison.**

| Magnet  | $v^a$<br>(m/s) | Dust load<br>(mg) | Rate<br>( $\mu\text{g}/\text{Sol}$ ) | Rate/area<br>( $\mu\text{g}/(\text{Sol}\cdot\text{cm}^2)$ ) |
|---------|----------------|-------------------|--------------------------------------|---|
| Capture | 2.2            | 21.7              | 79                                   | 16  |
|         | 2.7            | 19.2              | 70                                   | 14  |
| Filter  | 2.2            | 12.7              | 46                                   | 9.4   |
|         | 2.7            | 9.4               | 34                                   | 7.0   |

<sup>a</sup>Wind velocity

Increasing the wind speed leads to reduced capture of magnetic particles. The relative change in capture rate when increasing the wind speed from 2.2 m/s to 2.7 m/s is 11% and 26% for the Capture and Filter Magnets respectively. This difference reflects the better “filtering” capabilities of the Filter magnet [12].

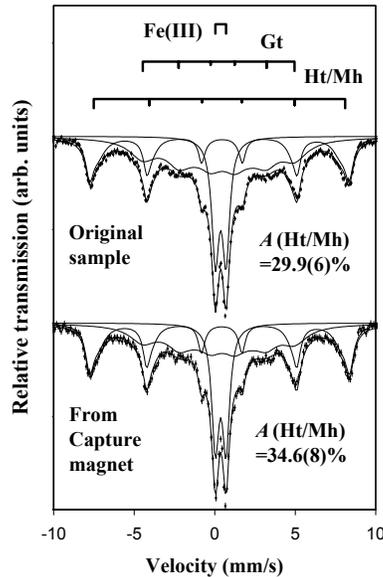
*Magnetic Properties.* The hysteresis properties of the dust are shown in Fig. 3. The Salten Skov reference soil used here is more magnetic than current estimates of the magnetic properties of the dust on Mars. The material that has accumulated to the magnets is more magnetic than the original material and the material that has accumulated to the Filter Magnet is more magnetic than the material that has accumulated to the Capture Magnet.



**Fig. 3:** Hysteresis curves of the Salten Skov reference sample, and samples collected from the magnets indicated. Values of the saturation magnetization,  $\sigma_s$ , obtained from analysis of the experimental data are shown in the insert.

The capture of magnetic particles by permanent magnets under Martian conditions is a complicated process, involving a number of parameters. Generally, the magnetic properties of the accumulated material will depend on the strength of the magnets in such a way that weak magnets accumulate the more strongly magnetic particles. The findings here are in accordance with the design criteria of the magnets [12].

*Mössbauer Spectroscopy.* Fig. 4 shows the Mössbauer spectra obtained.



**Fig. 4:** Mössbauer spectra of the Salten Skov reference sample and the material accumulated on the Capture Magnet.

The spectra have been analyzed in terms of three spectral components indicated in Fig. 4. [18]: A sextet labeled Gt, assigned to goethite, a sextet labeled Ht/Mh, assigned to maghemite/hematite mixtures and a quadrupole split component labeled Fe(III) assigned to ferric (super-) paramagnetic iron oxide(s). The sextet components have been analyzed with split-Lorentzian line shapes, which simulate the asymmetric spectral lines quite well and enable the determination of area fractions for the different components. We do not try to separate the hematite and maghemite components in view of their rather similar hyperfine parameters and the rather broad asymmetric line shapes.

Visual inspection of the spectra in Fig. 4 shows only minor differences between the spectra, and computer analysis is needed to extract the differences in the spectra. The results are given in Table 2.

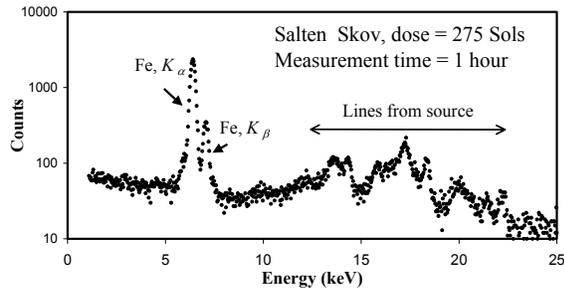
**Table 2:** Hyperfine parameters and relative spectral areas obtained from analysis of the spectra in Fig. 4. Labels in the table:  $B_{\text{hf}}$ : magnetic hyperfine field,  $\delta$ : isomer shift,  $\Delta E_Q$ : quadrupole splitting or shift.

| Parameters | Sample              |            |          |
|------------|---------------------|------------|----------|
|            | Reference           | Capture m. |          |
| Ht/Mh      | $B_{\text{hf}}$ (T) | 48.3(1)    | 48.4(1)  |
|            | $\delta$ (mm/s)     | 0.37(2)    | 0.37(3)  |
|            | $\Delta E_Q$ (mm/s) | -0.16(2)   | -0.13(2) |
|            | Area (%)            | 29.9(6)    | 34.6(8)  |
| Gt         | $B_{\text{hf}}$ (T) | 21(2)      | 21(3)    |
|            | $\delta$ (mm/s)     | 0.37(6)    | 0.37(9)  |
|            | $\Delta E_Q$ (mm/s) | -0.25(5)   | -0.25(5) |
|            | Area (%)            | 47(2)      | 23.7(3)  |
| Fe(III)    | $\delta$ (mm/s)     | 0.373(8)   | 0.37(2)  |
|            | $\Delta E_Q$ (mm/s) | 0.67(2)    | 0.67(2)  |
|            | Area (%)            | 23.0(3)    | 41(2)    |

The area ratio of the Ht/Mh component is larger in the material that has accumulated on the magnet, consistent with the interpretation that the material that give rise to the Ht/Mh sextet is the same material that gives the sample its magnetic properties. The quadrupole shift of the Ht/Mh component is slightly smaller for the material that has accumulated on the magnet. This is consistent with the interpretation that the material attracted by the magnet contains more maghemite ( $\Delta E_Q \approx 0$  mm/s) relative to hematite ( $\Delta E_Q \approx -0.2$  mm/s) than the original sample.

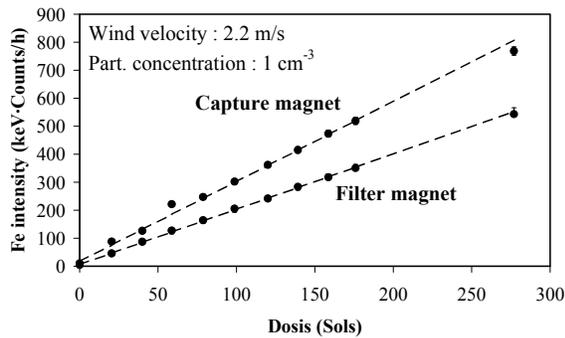
*XRF results.* Fig. 5 shows a typical XRF spectrum obtained. It shows notable emission at  $\sim 7$  keV, originating from the  $K_\alpha$  and  $K_\beta$  lines of iron. The lines at  $E > 12$  keV, originate from the source. Additionally the spectrum has lines from manganese on the left-hand shoulder of the  $K_\alpha$  line of Fe. On Mars, lines from alu-

aluminum, originating from the target surface, would dominate the spectrum.



**Fig. 5: XRF spectrum of dust on the Capture Magnet obtained for the measurement conditions indicated.**

Fig. 6 shows the intensity of the Fe lines as a function of dose obtained from 1 hour measurements of the Capture and Filter Magnets.



**Fig. 6: Signal in units of keV-Counts for 1 hour measurements as a function of dose for the Capture and Filter Magnets. Saturation level (infinitely thick layer) is around 4300 keV-Counts/h for the reference material.**

The ratio between the slopes of the curves in Fig. 6 is 1.45 while the ratio of the mass of the dust accumulated on the magnets is 1.7 (see Table 1), indicating that the dust accumulated to the Filter Magnet is more iron rich than the dust accumulated to the Capture Magnet.

**Discussion:** From these data and the error analysis, the sensitivity is easily estimated, and we find that the minimum amount of material that can be detected is of the order of a few  $\mu\text{g}$  for a measurement time of 10 hours. Taking into consideration the different experimental conditions on Mars (with  $\alpha$  particles) a careful estimate suggests that the Ti/Fe ratio could be determined with accuracy better than 30% when the magnet has accumulated 300  $\mu\text{g}$  of material.

We have performed wind tunnel experiments with both the Pathfinder Magnet Array and the Capture

Magnet. Visual inspection suggests that the Capture Magnet collects dust 2–4 times more efficiently on unit area than the strongest magnet of the Pathfinder mission. Using dust accumulation rates determined for the strongest magnet of the Pathfinder Magnet Array on Mars [6], suggests that the Capture Magnet will collect dust at a rate of  $\sim 60 \mu\text{g}/\text{Sol}$ . A determination of the Ti/Fe ratio with the accuracy stated above will thus be possible few sols into the mission.

**Conclusions and outlook:** The data presented here demonstrates how the analysis of the data that (hopefully) will be obtained from Mars can be performed. The amount of material accumulated onto the magnets will be estimated in three different ways: (1) Optically, both by utilizing the change in color of the target and by using the surface markings. (2) By using the signal obtained in the APXS measurements, both relative to the lines of aluminum and absolute counts in the spectrum. (3) By using the relative signal intensity of the Mössbauer spectra. All techniques are sensitive to different physical properties of the dust and comparison of the results may give deeper insight into the properties of the dust.

APXS measurements with adequate accuracy to elucidate fundamental questions regarding the soil formation processes on Mars will be possible few sols into the mission.

We are continuing these investigations, using analogues of different nature and varying magnetic properties. The results will enhance our knowledge on what may be learned from the investigations on Mars.

**References:** [1] Hargraves R. B. et al. (1977) *JGR*, 82, 4547–4558. [2] Gunnlaugsson H. P. et al. (1998) *Planet. Space Sci.*, 46, 449–459. [3] Hargraves R. B. et al. (1979) *JGR*, 104(E4), 8379–8384. [4] Hviid S. F. et al. (1997) *Science*, 278, 1768–1770. [5] Madsen M. B. et al. (1999) *JGR*, 104(E1), 8761–8384. [6] Gunnlaugsson H. P. (2000) *Planet. Space Sci.*, 48, 1491–1504. [7] Coey J. M. D. et al. (1990) *JGR*, 95, 14423–14425. [8] Morris R. V. et al. (1990) *JGR*, 95, 14427–14434. [9] Knudsen J. M. et al. (1991) *Hyp. Int.*, 68, 83–94. [10] Madsen M. B. et al. (1995) *Hyp. Int.*, 95, 291–304. [11] Squyres S. et al (2003) *JGR*, (Submitted). [12] Madsen M. B. et al (2003) *JGR*, (Submitted). [13] Klingelhöfer G. et al (2003) *JGR*, (Submitted). [14] Rieder R. et al (2003) *JGR*, (Submitted). [15] Gorevan S. et al. (2003) *JGR*, (Submitted). [16] Binau C.S. et al. (2003) *Planet. Space Sci.*, (Submitted). [17] Merrison J. P. et al. (2002) *JGR*, 107, 5133, doi:10.1029/2001JE001807. [18] Gunnlaugsson H. P. (2003) *Hyp. Int.*, (In press). [19] Nørnberg P. et al. (2003) Manuscript in preparation.