THE EFFECT OF BORON ON ACTIVE NEUTRON MEASUREMENTS: APPLICATIONS FOR THE MARS SCIENCE LABORATORY DYNAMIC ALBEDO OF NEUTRONS INSTRUMENT.
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Introduction: The primary objective of the Dynamic Albedo of Neutrons (DAN) experiment onboard the Mars Science Laboratory (MSL) rover Curiosity is to assess both hydrogen abundance and burial depth as the rover traverses the Martian surface [1]. DAN uses a Pulsed Neutron Generator (PNG) as a neutron source, coupled with a thermal neutron detector composed of two He-3 proportional counters. One of the He-3 counter is covered with a thin cadmium foil to absorb thermal neutrons. Because He-3 proportional counters are sensitive to thermal and epithermal neutrons, the difference between the bare counter and the shielded counter is therefore a measure of the thermal neutron count rate. There are two modes in which the DAN instrument can operate: passive and active. When DAN is in active mode, the PNG is turned on and emits pulses of 14.1 MeV neutrons in roughly all directions (4 π). When DAN is in passive mode, the PNG is off so only neutrons produced from galactic cosmic rays and those emitted by the multi-mission radioisotope thermoelectric generator act as neutron source. Neutrons are subsequently moderated in the Martian soil and detected by the DAN thermal neutron detector. The analysis presented in this paper was done for the active mode only.

Because hydrogen is a light element, it is an efficient moderator for neutrons. By measuring thermal neutrons that are moderated and scattered out of the surface of the soil, it is possible to quantify the hydrogen content [1]. However, other elements, such as boron, have a high cross section for thermal neutron capture (Fig. 1) and can affect the thermal neutron flux measured by DAN. In particular, B-10 has a capture cross section of 3840 barns at 0.025 eV and represent 19.8% of the natural elemental abundance.

While Fe is a typical rock forming element, and occurs in consistent amounts throughout the traverse, soluble elements such as B and Cl are concentrated in areas with a lot of water. Hence Cl and B are good tracers of past under-ground water activity. The average rock in Gale crater contains ~20 wt% FeO, with a normal range of ~18-23 wt% FeO, while the range is ~ 0.5-1.5 wt% Cl. Recently, the MSL ChemCam instrument has shown high concentrations of B in the veins of the Murray formation and Yellowknife Bay at concentrations of 100 to 500 ppm [2]. While 500 ppm might be the upper limit of B in a particular clay, the fraction of B-bearing species in the rock is ~50-75%, which shows that the bulk amount of B in the rock is ~50-400 ppm. A new study by Nellessen et al. [3] shows the bulk bedrock content could be as high as 500 ppm.

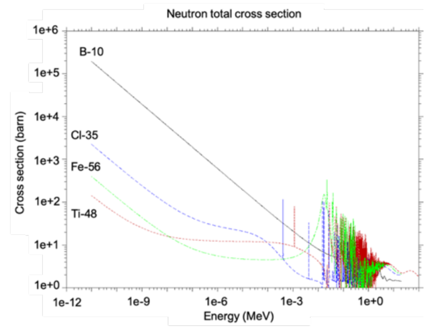

Figure 1. *Total neutron cross sections for Ti-48, Fe-56, Cl-35, and B-10.*

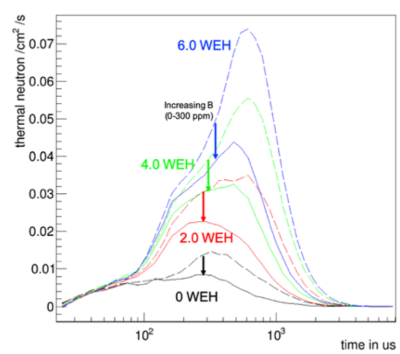

Figure 2. *Simulated neutron die-away curves as a function of water equivalent hydrogen (WEH) and increasing boron. Each color represents a fixed WEH, and for each fixed WEH, the B content varies from 0 to 300 ppm. The dotted line for each WEH represents 0 ppm B. The solid line for each WEH represents 300 ppm B.*

Previous studies by Hardgrove et al. [4] and Gasda et al. [5] reported the influence of neutron absorbing element (Cl, and B, respectively) on the thermal neutron count rate measured by DAN and found that the presence of these elements in the surface can influence the interpretation of H content if their abundance is not known and correctly taken into account. Because of the high capture cross section of B-10, the number of neutrons that are captured in the soil increases with increasing B, resulting in reduced count rates observed by the DAN thermal neutron detector.

Count Rate and Uncertainty: The neutron die-away curves were simulated using the MCNP6 code [6]. Fig. 2 shows that the thermal neutron count rate measured by DAN decreases as the amount of B increases. Fig. 3 shows the increase of uncertainty in the measurement due to the presence of B after a typical measurement of 20 minutes in active mode.

Curve Similarity: The presence of B can reduce the thermal neutron count rate detected by the DAN detector and, if not properly accounted for, lead to overestimates of H content. In the right panel of Fig. 4, we show that the die-away curve for 6 wt% H_2O with 300 ppm of B is similar to the die-away curve for 2 wt% H_2O with 40 ppm of B (right panel). Hence, in the presence of a high content of B, the WEH content can be interpreted as much lower if the content of B is not known and not taken into account.

With improved counting statistics from longer measurement times, more accurate quantification of H content in the presence of absorbers could potentially be made based on the shape of the thermal neutron die-away curve but was not part of the study here.

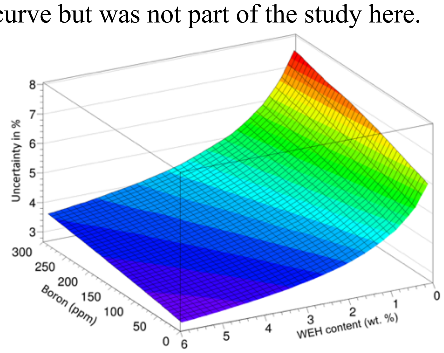

Figure 3. *Uncertainty (% in counts) as a function of WEH and B content after a 20-minute DAN active measurement.*

In order to study the similarity or difference between 2 data sets, we calculated the following sum S:

$$\boxed{S = \sum_{i=0}^{n} \frac{\| N_1 - N_2 \|_i}{\sqrt{\sigma_1^2 + \sigma_2^2}_{\,i}}},$$

where N_1 and N_2 are the thermal neutron counts at each time after the pulse, i is the time after the pulse, and σ_1 and σ_2 are the errors associated with each counts. The sum increases as the difference between two curves increases as shown in Fig. 4, left panel. On the contrary, the sum decreases as the similarity between two curves increases, as shown in Fig. 4, right panel.

In Fig. 5, we studied the similarity between the data set for 2 wt% H_2O with 0 ppm B and all other data sets that were simulated. Similar calculations were done with the other data sets and the results will be presented.

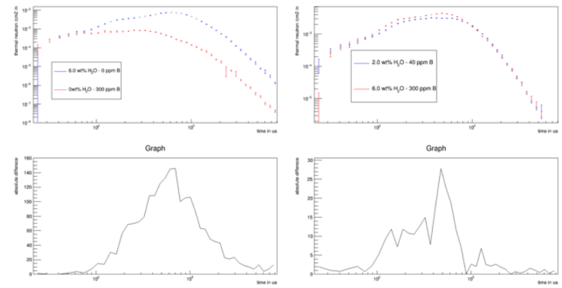

Figure 4. *Example of two different data sets (left panel), and two similar data sets (right panel). The calculated sum increases as the difference increases.*

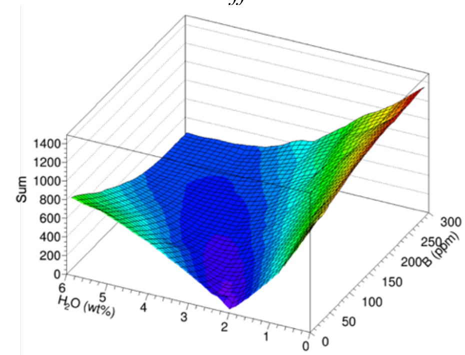

Figure 5. *Calculated sum S for 2 wt% H_2O with 0 ppm B and all other data sets that were simulated.*

High absorption cross section elements such as Cl and B can strongly influence the profile of thermal neutron die-away curves. This work demonstrates the importance of knowing the presence of elements with strong absorption cross section to interpreting the content of H as accurately as possible.

Additionally, strong reductions in thermal neutron flux can also be used to identify possible geochemical variations along a rover traverse. DAN observations coupled with other instruments (such as ChemCam) can be used to constrain the amount of B in the bulk rock. Localized (i.e. vein) vs bulk-rock measurements of boron abundance can help improve our understanding of water activity and groundwater pH on ancient Mars.

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References: [1] Litvak et al., (2008) Astrobio., 8. [2] Gasda et al., (2017) Geophysical Research Letters, 44.17, 8739-8748. [3] Nellessen et al., (2020) *LPS LI.* [4] Hardgrove et al., (2011) *LPS XLII,* Abstract #2135. [5] Gasda et al., (2019) AGU Fall meeting, Abstract #P31A-3427 [6] Goorley et al., (2012) *Nuclear Technology, 180.3,* 298-315.