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Title: TEMPERATURE DEPENDENCE OF THERMAL NEUTRONS FROM THE MOON

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ABSTRACT

Planetary thermal neutron fluxes provide a sensitive proxy for mafic and feldspathic terranes, and are also necessary for translating measured gamma-ray line strengths to elemental abundances. Both functions require a model for near surface temperatures and a knowledge of the dependence of thermal neutron flux on temperature. We have explored this dependence for a representative sample of lunar soil compositions and surface temperatures using MCNP™. For all soil samples, the neutron density is found to be independent of temperature, in accord with neutron moderation theory. The thermal neutron flux, however, does vary with temperature in a way that depends on Δ, the ratio of macroscopic absorption to energy-loss cross sections of soil compositions. The weakest dependence is for the largest Δ (which corresponds to the Apollo 17 high Ti basalt in our soil selection), and the largest dependence is for the lowest Δ (which corresponds to ferroan anorthosite, [FAN] in our selection). For the lunar model simulated, the depth at which the thermal neutron population is most sensitive to temperature is ~30 g/cm^2.

I. INTRODUCTION

The information content of thermal neutrons from planetary surfaces stems from several parameters that shape equilibrium neutron flux distributions. These parameters in turn, reflect three major processes that control the shapes of neutron energy distributions; 1) the neutron production rate by galactic cosmic rays, 2) their moderation to lower energy through primarily elastic energy-loss collisions, and 3) their absorption at thermal energies. The first process can be eliminated by construction of the ratio of thermal to epithermal neutron fluxes. This ratio is then determined by only one parameter, the ratio of the macroscopic absorption to energy-loss cross section of surface soils. The variation of this parameter for a variety of soils found on planetary surfaces is large (amounting to more than two orders of magnitude). It thereby provides a sensitive discriminator between mafic and feldspathic lithologies and also to the presence of minute amounts of hydrogen (having a detection threshold of about 20 ppm).[1-3]

Knowledge of thermal neutron distributions also has another important application. A well-developed technique to determine the composition of surface soils is to measure the intensity of gamma-ray lines stemming from the absorption of thermal neutrons.[4,5] One example is the Fe(n,γ) reaction that produces 7.645 and 7.63 MeV gamma-ray lines, which are readily measurable. Translation of these line strengths to Fe abundance requires knowledge of the neutron number density. This quantity, in turn, can be determined from a measurement of the flux of thermal and epithermal neutrons that leak outward from planetary surface layers to space. Although measurement of these neutron fluxes for planetary exploration is straight forward using a variety of techniques,[1,6] the translation of these fluxes to useful information requires knowledge of the physical temperature of surface layers and a knowledge of its effect on the flux of escaping neutrons.

We address this last problem in the present study by simulating the equilibrium neutron flux distributions for a

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variety of depth-dependent temperature profiles and soil chemistries using the Monte Carlo N-Particle (MCNP) code developed at Los Alamos.[7] The computational technique applied in our simulations is first presented in section II. The parameter range of our simulations is also presented there. The results of the simulations and their analysis in terms of the relationship between thermal-neutron flux intensities and the depth distribution of surface temperatures for a representative sample of chemistries is given in section III. These results are summarized in section IV.

II. SIMULATIONS

A. Neutron Transport Simulations

Monte Carlo transport simulations were performed with Versions 4XU[8] and 4C[9] of MCNP. The neutron energy spectrum and depth distribution were obtained from previous calculations and are plotted in Figs. 1a and 1b.

Six lunar soil compositions were modeled: Apollo 11 (AP11), Apollo 12 (AP12), Apollo 17 (AP17), Luna 20, ferroan anorthosite (FAN), and Apollo 17 high Ti basalt (AP17HiTiBa). In each case we used nominal weight fractions of SiO_2, TiO_2, Al_2O_3, FeO, MgO, CaO, Na_2O, Mn, Sm, and Gd.[10] In addition, we performed calculations for a mixture of 90% FAN and 10% water. In all cases, we used a soil density of 1 g/cm^3.

Neutron cross sections were all based on ENDF/B-VI evaluations. For all but isotopes of Sm and Gd, the cross sections were from the ENDF60 library.[11] MCNP cross sections for 7 isotopes of Sm and 7 isotopes of Gd were prepared specifically for this study. All cross sections were processed at room temperature.

Calculations for each soil composition were performed at four temperatures: 100, 200, 300, and 400 degrees Kelvin. The temperature-dependence of cross sections in MCNP is handled by modifying the elastic scattering cross section using a free-gas model. Similarly, kinematics are modeled based on free-gas theory. Absorption cross sections are not modified, based on the assumption of a 1/v dependence. Although this approximation fails for isotopes with large resonances at low neutron energies, such as ^{149}Sm and ^{157}Gd, we did not believe it necessary to generate cross sections broadened to various temperatures.

Detailed neutron leakage spectra were calculated from 10^{-10} to 10^{-4} MeV. All simulations used a minimum of 650,000 source neutrons. Typical running times were ~ 4 hours on a Sun Ultra 1.

B. Detector Response Simulations

The detailed leakage spectra calculated by MCNP were used in combination with detector response functions to arrive at total simulated thermal and epithermal count rates.

The specific detectors considered were those comprising the Lunar Prospector (LP) neutron spectrometer (NS). Thermal and epithermal neutrons are measured from lunar orbit using two ^{3}He-filled gas proportional counters and associated electronics.[12] One of the counters is covered with a 0.63-mm-thick sheet of Cd and used to determine the epithermal counts. The other detector is wrapped with Sn; the difference in counting rates from the two detectors yields the thermal counts.

The detector response functions used in this study are from previous MCNP calculations and are shown in Figure 2. Using these response functions with the calculated MCNP spectra allows us to arrive at a simulated thermal count rate and a simulated epithermal count rate for each combination of soil composition and temperature.

III. RESULTS

A. Neutron Flux as a Function of Temperature

The energy distribution of the neutron flux at the lunar surface can be described by a single power law in the epithermal range, and a Maxwellian in the thermal range. The relative amplitudes of each of the components depend on composition and temperature.

Of the six lunar soil compositions investigated, the FAN results showed the largest dependence on temperature (see Fig. 3A). The reason for this is that FAN has minimal concentrations of highly-absorbing materials; therefore the thermal neutrons are best able to equilibrate with the target nuclei at velocities (neutron energies) representative of the medium.

The least dependence of calculated neutron flux on temperature was observed for the Apollo 17 high Ti basalt case (see Fig. 3B). This composition includes substantial amounts of Fe and Ti. The large absorption cross sections of these materials tend to offset the thermal neutron dependency on scattering kinematics, and hence on material temperature.

B. Thermal and Epithermal Count Rates

As described in section 2B, we convoluted the MCNP calculated neutron leakage spectra with thermal and epithermal detector response functions to obtain thermal and epithermal count rates for each model. A plot of the temperature-dependence of the resulting thermal neutron count rates is shown in Fig. 4A. Note again that the FAN results show the most dependence on temperature of the six lunar soils considered. The range of variation of thermal counts for FAN between T=100 K and 400 K was about 25%, which is far less than what might be expected for a pure thermal population having a constant density (flux is proportional to $T^{0.5}$). The reason for the reduced sensitivity of thermal counts to temperature is that the flux of epithermal neutrons fills in the energy range vacated by the thermal population as T decreases.

In Fig. 4B, we plot the temperature-dependence of the epithermal neutron count rates. Although the 10% water plus FAN case is not a realistic lunar scenario, note how drastically the hydrogen depletes the epithermal neutrons in this case. Finally, the temperature-dependence of the ratio of the thermal to epithermal count rates is shown in Fig. 4C.

Delta (Δ) is a convenient parameter to describe neutronic properties of a material. We define Δ as the ratio of macroscopic absorption to energy-loss cross sections. We have determined Δ for each of the six lunar compositions modeled. Using these values, and the results of Fig. 4C, we are able to develop a power law in temperature that describes the relationship between Δ and the ratio of the thermal to epithermal neutron counts (see Fig. 5). Therefore, if the material temperature is known, and the thermal and epithermal count rates are measured, then Δ can be determined.

After Δ is determined, it is possible to go one step further and construct a relationship that results in neutron density. The relationship is a function of temperature and the total neutron count rate (thermal plus epithermal). Figs. 6A and 6B show how well the constructed power law reproduces data calculated in this study.

C. Non-Uniform Temperature Distributions

All results thus far have been for models where the material temperature has been constant. More realistically, the temperature of the lunar soil will be at its extreme (minimum or maximum) at the surface and will then vary with depth until reaching some constant value. To explore this effect, we performed additional calculations with FAN wherein the temperature was varied linearly as a function of depth. The result of this study was that thermal neutron counts at the surface were characterized by the temperature at an effective depth of about 30 g/cm^2 below the surface, which corresponds to a physical depth of 20 cm for a density of 1.5 g/cm^3.

IV. SUMMARY

We have used MCNP to explore the temperature-dependence of galactic cosmic ray induced neutron leakage from several typical lunar soil compositions. As expected, the neutron number density at the surface is independent of temperature. However, the neutron flux at the surface is a function of temperature; the variation of thermal neutron flux with temperature depends inversely on the ratio of macroscopic absorption to energy-loss cross sections. The range of variation of thermal neutron flux for a FAN composition was found to be about 25% over the temperature range from 100 to 400 degrees Kelvin. The effective temperature derived from thermal neutrons measured at the surface corresponds to a depth of about 30 g/cm^2, which is a physical depth of 20 cm for a density of 1.5 g/cm^3. This depth is below the thermal wave on the Moon so that thermal neutron fluxes measured at orbit should not respond to diurnal variation of surface temperatures.

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FIGURE CAPTIONS

Fig. 1: Data used for neutron source distributions. Fig. 1A shows the energy spectrum and Fig. 1B shows the depth dependence of the source intensity (1 g/cm^3 soil density).

Fig. 2: Thermal and epithermal detector response functions used to convert calculated flux spectra to count rates.

Fig. 3: Calculated neutron leakage spectra. Fig. 3A is for FAN, Fig. 3B is for Apollo 17 high TI basalt. In both cases, results are shown for 100, 200, 300, and 400 degrees Kelvin.

Fig. 4: Temperature-dependent count rates for the compositions considered. Figure 4A shows thermal count rates, Fig. 4B shows epithermal count rates, and Fig. 4C shows the ratio of thermal to epithermal count rates.

Fig. 5: Power law constants relating delta (the ratio of macroscopic absorption to energy-loss cross sections) to the ratio of thermal to epithermal neutrons.

Fig. 6: Power law constants relating the neutron density to the sum of the thermal and epithermal count rates. The power law index is shown in Fig. 6A and the power law amplitude in Fig. 6B.

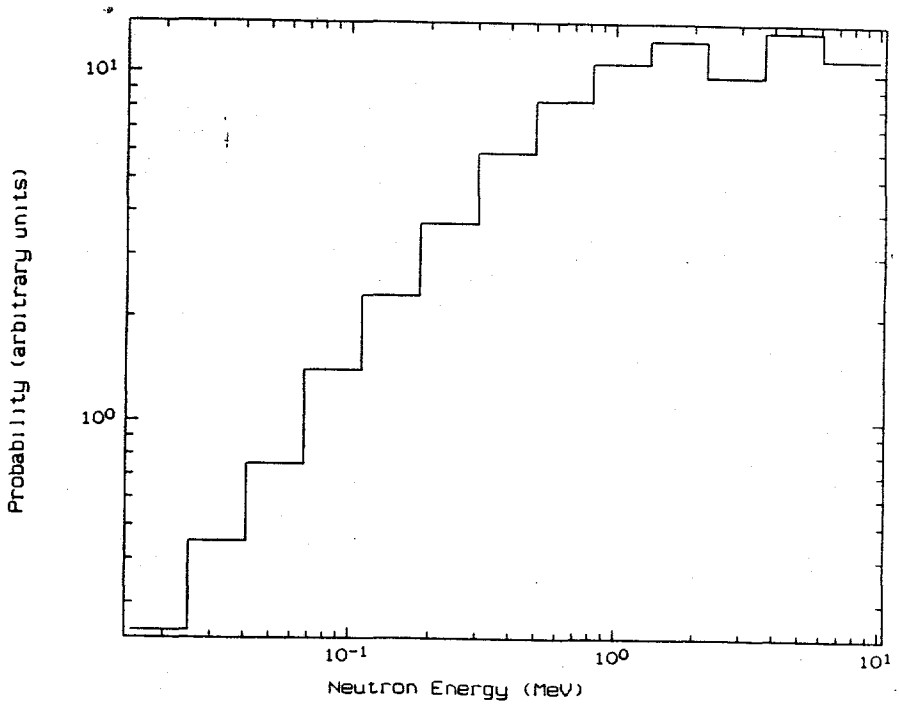

Figure 1A

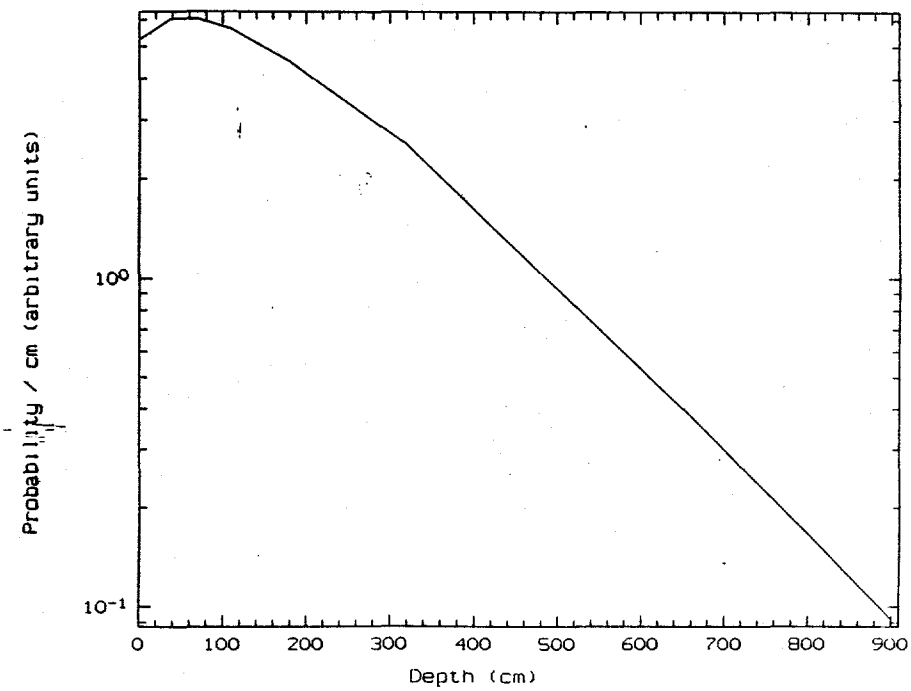

Figure 1B

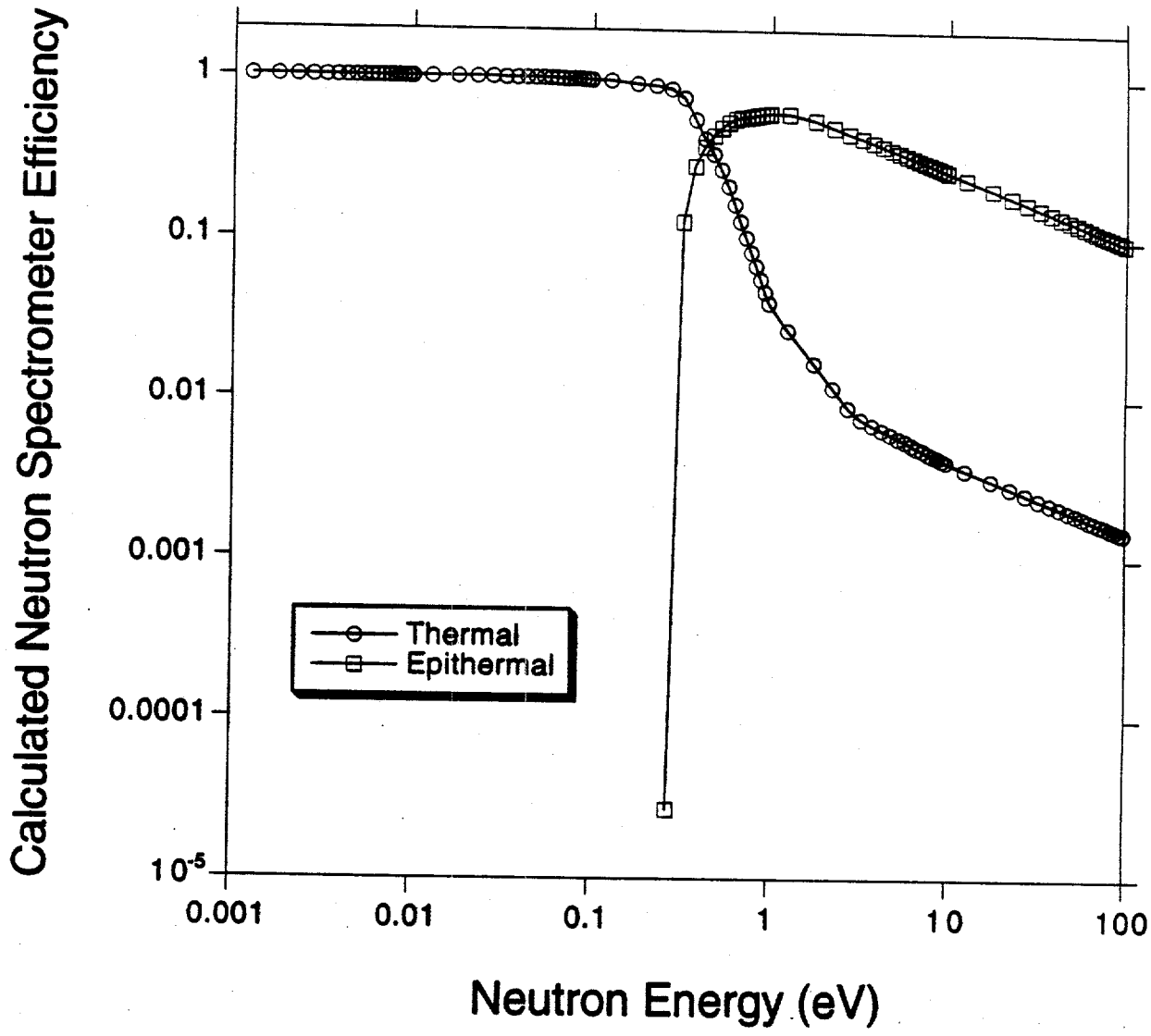
Calculated Neutron Spectrometer Efficiency
1
0.1
0.01
0.001
0.0001
10-5
0.001
0.01
0.1
1
10
100
Neutron Energy (eV)
Thermal
Epithermal

Figure 2

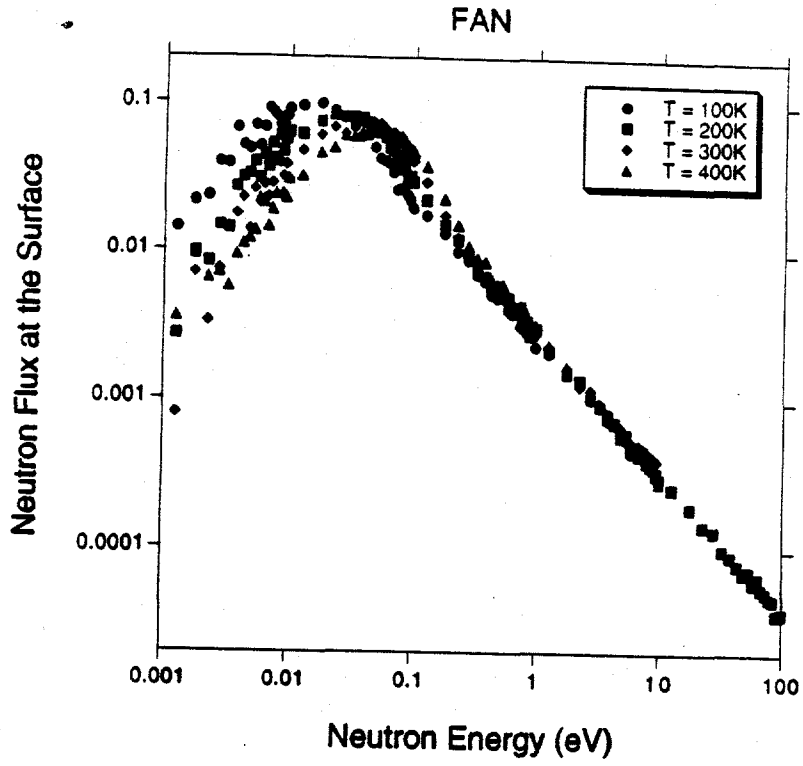

Figure 3A

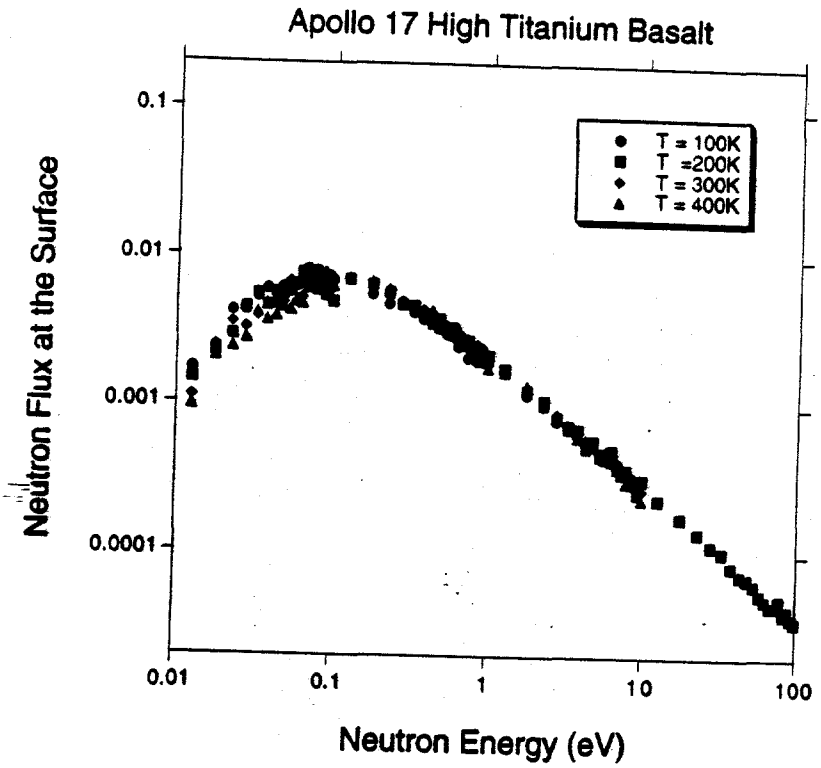

Figure 3B

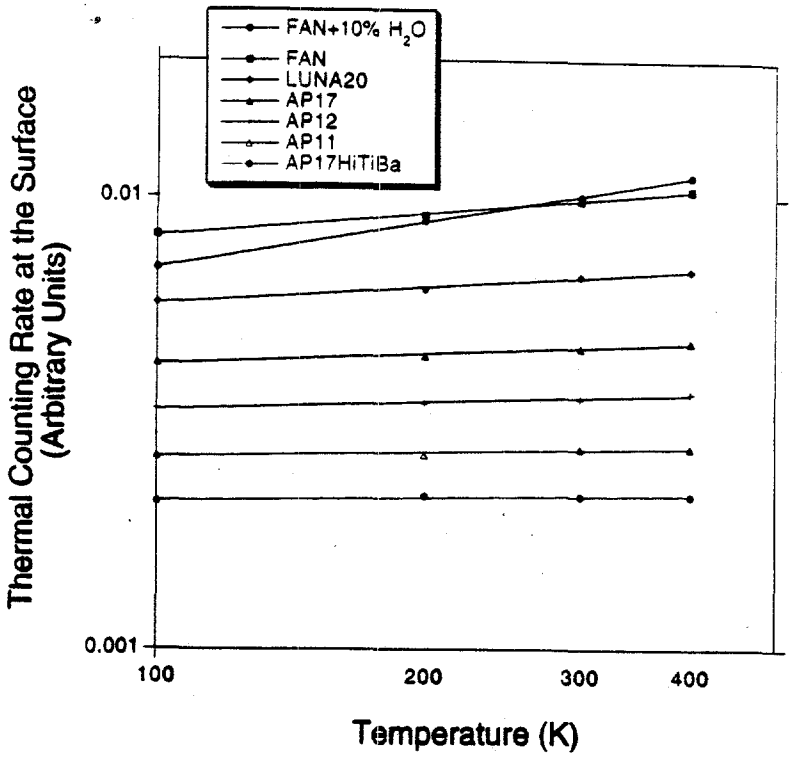

Figure 4A

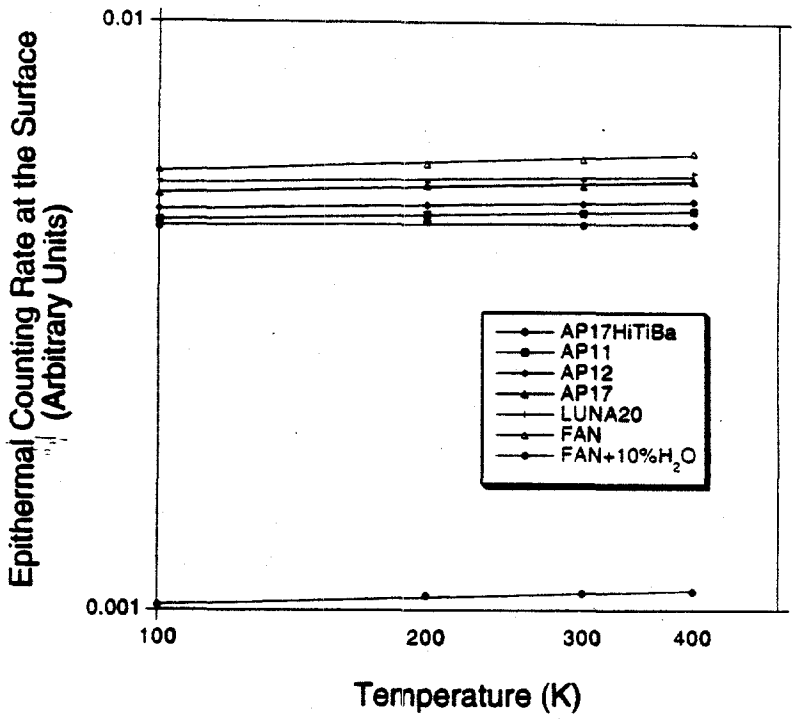

Figure 4B

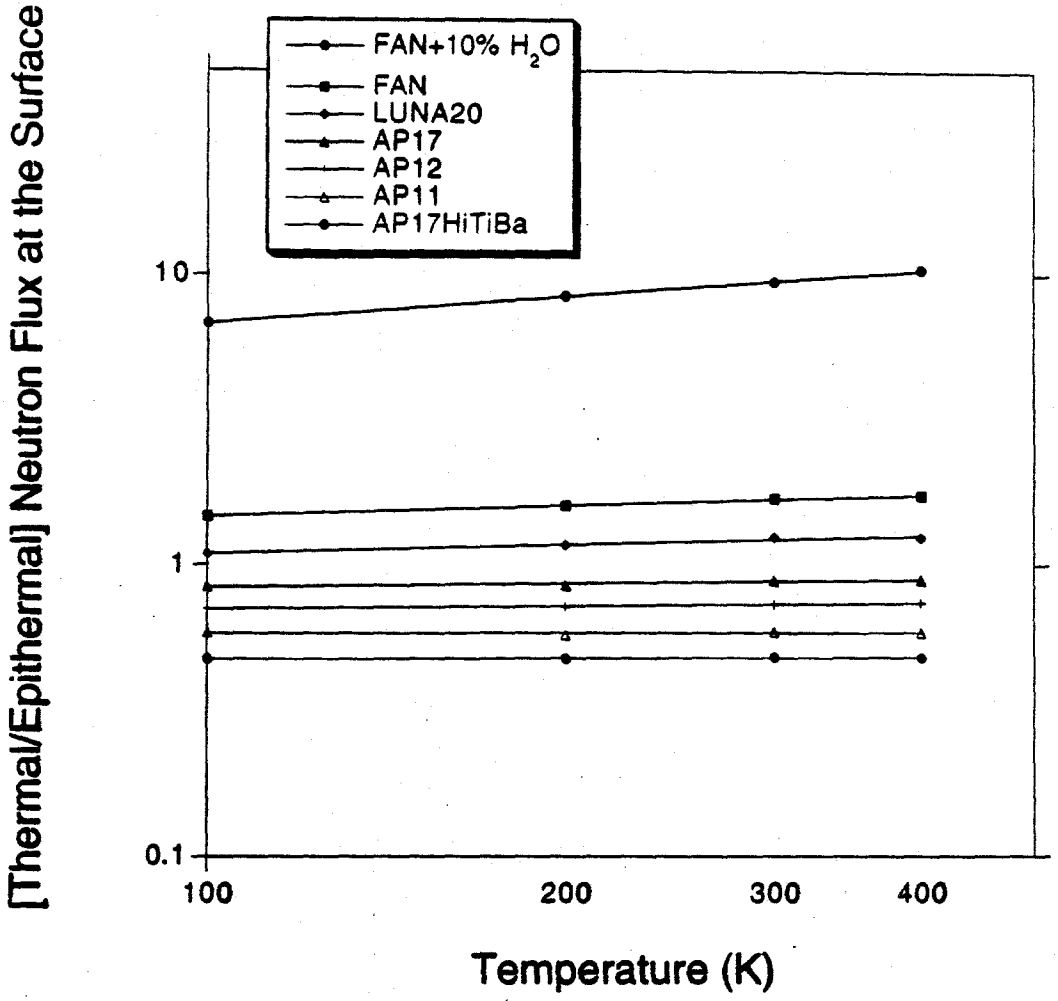
FAN+10% H_2O
FAN
LUNA20
AP17
AP12
AP11
AP17HiTiBa
10
1
0.1
100
200
300
400
[Thermal/Epithermal] Neutron Flux at the Surface
Temperature (K)

Figure 4C

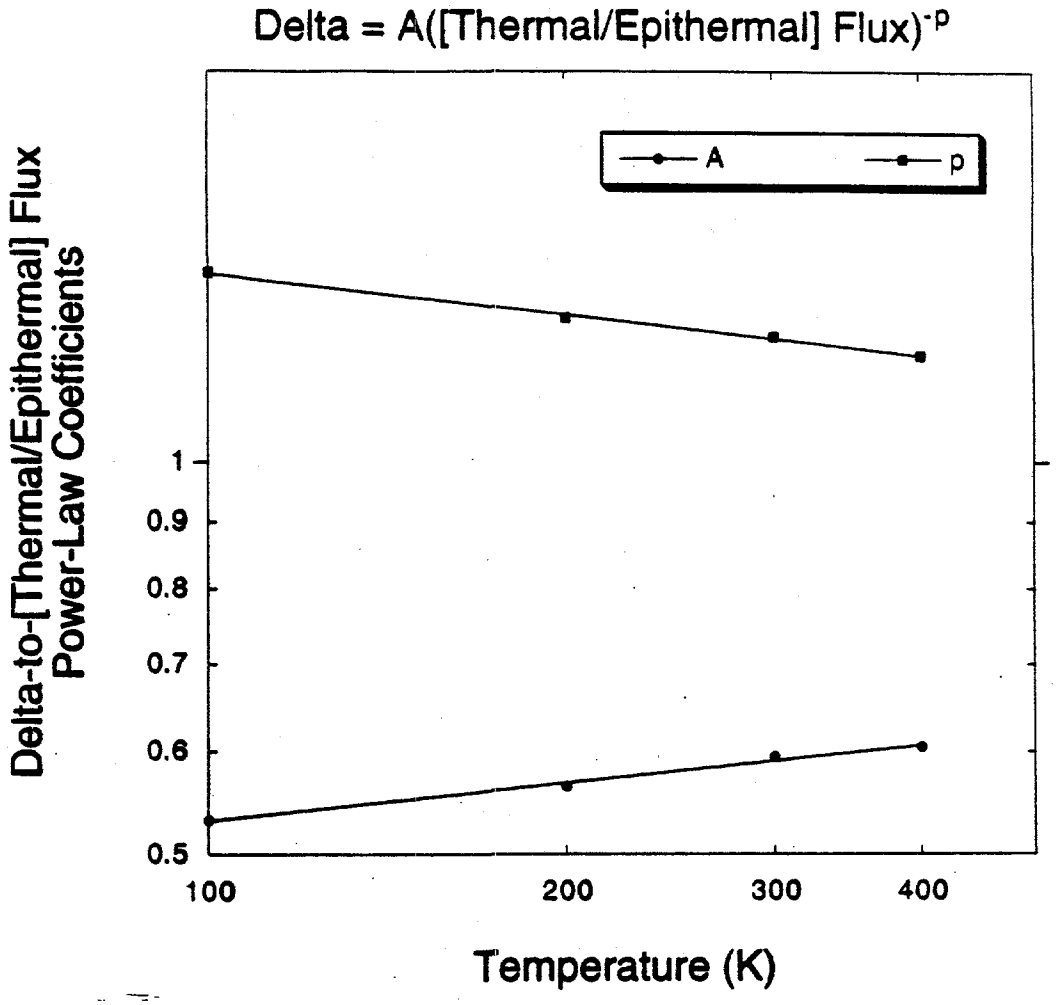
Delta = A([Thermal/Epithermal] Flux)^-p
Delta-to-[Thermal/Epithermal] Flux
Power-Law Coefficients
A
p
1
0.9
0.8
0.7
0.6
0.5
100
200
300
400
Temperature (K)

Figure 5

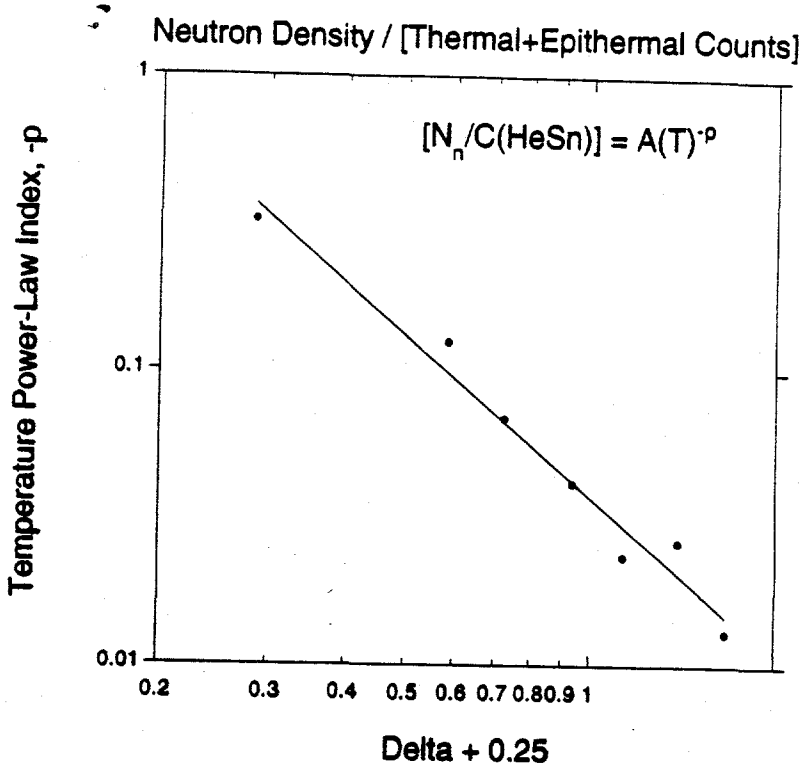

Figure 6A

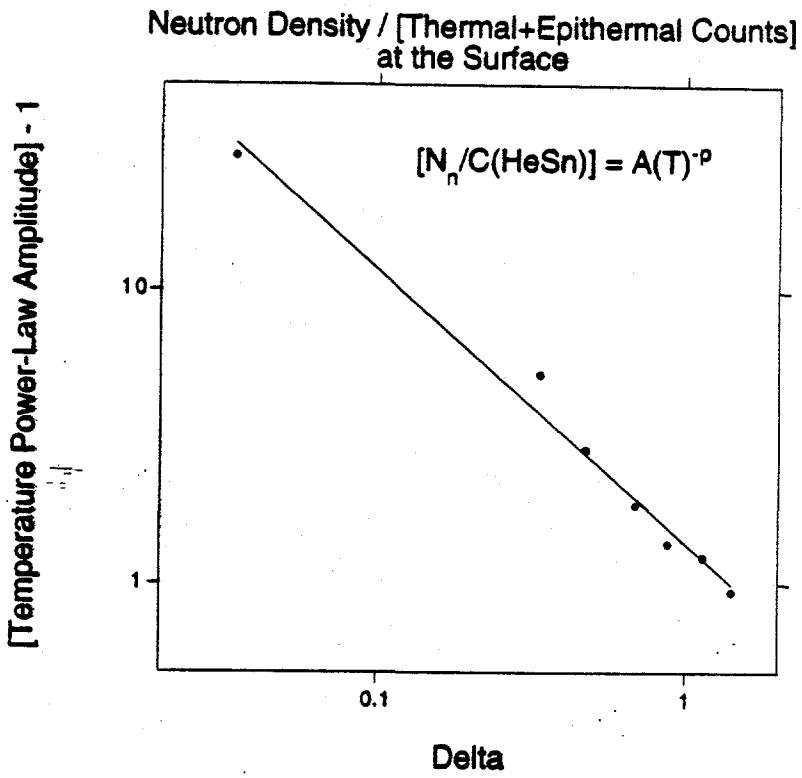

Figure 6B