First Semi Annual Report
for PIDDP Program
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# X-Ray Remote Sensing and In-Situ Spectroscopy for Planetary Exploration Missions

and

# Gamma-Ray Remote Sensing and In-Situ Spectroscopy for Planetary Exploration Missions

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Abstract:

Detectors that will be used for planetary missions must have their responses calibrated in a reproducible manner. A calibration facility is being constructed at Schlumberger-Doll Research for Gamma- and X- Ray detectors. With this facility the detector response can be determined in an invariant and reproducible fashion. Initial use of the facility is expected for the MARS94 detectors.

Work is continuing to better understand the rare earth oxyorthosilicates and to define their characteristics. This will allow a better use of these scintillators for planetary missions. In a survey of scintillating materials two scintillators were identified as promising candidates besides GSO, LSO, and YSO. These are CdWO4 and CsI(Tl). It will be investigated, if a detector with a better overall performance can be assembled with various photon converters.

Considerable progress was achieved in photomultiplier design. The length of an 1" diameter PMT could be reduced from 4.2" to 2.5" without performance degradation. This technology is being employed in the gamma-ray detector for the NEAR project. A further weight and size reduction of the detector package can be achieved with miniaturized integrated power supplies.

# Six Month PIDDP Report on Gamma-Ray and X-Ray Spectroscopy

## Introduction

During the initial six months of this program, a number of different studies have been initiated. In all cases, they are focused on the fundamentals of detector properties, physics of planetary spectroscopic measurements, and the improvements that can be obtained with the use of a neutron generator on a planetary surface, all for improving the determination of elemental concentrations that can be related to the lithological constituents of the body under study. While a number of small efforts have also been made, e.g. study of detector properties at 150 K for a possible comet penetrator with W. Boynton - U. of Arizona, the primary studies in this time period have been on obtaining a better understanding of the scintillation mechanisms in the cerium-doped rare-earth oxyorthosilicates to better be able to predict their performance for different planetary missions, a better determination of the spectroscopic potential for measurements made with a neutron generator, a detector calibration and response characterization facility, and a study of a Fourier transform technique for including the Compton background in the analysis of an elemental response with a germanium detector, such as was planned for Mars Observer. In addition, a survey of all known scintillators has been initiated with a goal of determining optimum combinations of scintillator and photon converters to obtain the best possible detector system for particular planetary measurement requirements. During the past decade Schlumberger developed a line of rugged, high temperature photomultipliers for well logging applications. This technology together with highly efficient photocathodes was applied for a new photoconverter, a much more compact photomultiplier tube, which has already been implemented for the NEAR detector. Finally, a study is being undertaken to combine the best features of a Schlumberger and a GSFC high voltage system to obtain a new design that satisfies the requirements for high voltage generation for both neutron and X-ray generators in a space environment.

## Detector Calibration and Response Characterization Facility

Detectors that will be used for planetary missions must have their responses calibrated in a reproducible manner, so that the information obtained during the mission can be better analyzed. In addition, it is important to characterize a detector system at uneven portions of its life cycle, for example after exposure to different amounts of radiation. The change in a detectors response can be well-determined in the laboratory, if an invariant reproducible facility exists that is unaltered over time. In addition, it is important that the facility is sufficiently flexible to permit the detector system to have its response to different stimuli, i.e. gamma rays of widely differing energies from different elemental sources, well characterized. This permits

a critical experimental determination of spectral response to an elemental source and is a necessary component for the analysis of the data obtained on the mission. Such measurements can also be used to benchmark Monte Carlo calculations that may be necessary to obtain final detector responses, either from an unplanned alteration in the detector response after launch or because of an inability to exactly simulate the planetary measurement environment in the laboratory.

A design has been completed for such a calibration and response characterization facility at Schlumberger-Doll Research for all types of gamma-ray (and x-ray) detectors that may be used for planetary measurement, whether orbital or on the planetary body. Neutron sources, either small D,T accelerators or isotopic sources, can be accurately positioned in a number of locations to obtain the desired response. The design also allows for the use of a compact x-ray generator. There is a 96% efficient germanium detector (Resolution ~ 2.1 keV) that is continuously available to insure stability of the electronics and geometry. The main calibration facility will be constructed of plywood and about 1500 lbs. of JSC-1 lunar simulant (obtained with the assistance of Texas A&M and JPL). There is a side-mounted arrangement to position the center of the front face of all detectors in a reproducible geometry. This design is shown in Figure 1. There will also be a facility filled with calcite that will allow response characterization to be obtained for arbitrary elements by "salting" the container with sealed samples of any elemental composition desired. There will also be other similar samples for obtaining detector responses in different mixes of elemental concentrations. The facility should be available for use in about 1-2 months.

Initial use of the facility is expected to be the MARS 94 detectors. The facility will then also be available for calibrating other detectors as well as arrays of detectors such as the NEAR detector with its central NaI(Tl) crystal surrounded with a large BGO crystal.

## The Scintillation Mechanisms in Cerium-Doped Rare-Earth Oxyorthosilicates

The cerium-doped rare-earth oxyorthosilicates are an interesting recently discovered family of single crystal scintillators that have many useful properties when using them as gamma-ray detectors. There are currently three established members of this family, a relatively light one based on yttrium, YSO,[1] and heavy ones based on gadolinium, GSO,[2] and lutetium, LSO.[3] All of these materials have relatively fast scintillation decays allowing high count rate capabilities without dead time and pile up corrections and appear to be at least reasonably resistant to radiation damage. However, the scintillation properties of these materials are not known. A further complication is that these materials have two different crystal structures. To make optimum use of such materials as possible detectors for planetary measurements, it is important to understand the scintillation mechanism of these materials to reliably predict their performance during the actual measurements.

The first of the cerium-doped rare-earth oxyorthosilicates to be used as a gamma-ray detector, GSO, has been extensively studied at Hitachi Chemical Company, the inventors of the material, and by us at Schlumberger-Doll Research, and at the National Synchrotron Light Source at Brookhaven National Laboratory, in collaboration with a group at California Institute of Technology. Through this effort,

we have established a model that describes the scintillation properties of GSO. This allows a better use of GSO for planetary measurements as the response can be predicted under any measurement condition. Work is continuing to better understand LSO, the heaviest of this type of detector, and potentially the best for measurements at temperatures below 300 K. A sample of GSO was irradiated and the detector characteristics were essentially unchanged. We expect to begin radiation studies on LSO in the next six months.

## Elemental Concentrations Determined With a Neutron Generator and a Gamma-Ray Detector

To better understand the potential for the use of pulsed neutron generators with landers, rovers, and penetrators, a laboratory model was constructed to simulate the surface of Venus. The elemental composition of the laboratory model was intended to simulate the analysis obtained by the Venera 14 lander. This comparison is shown in Table 1.

| Element | Venera 14 measurements | Venusian simulant |
|---|---|---|
| Magnesium | 4.9 | 4.3 |
| Aluminum | 9.5 | 7.9 |
| Silicon | 22.7 | 19.5 |
| Potassium | 0.17 | 0.65 |
| Calcium | 7.4 | 7.2 |
| Titanium | 0.75 | 0.75 |
| Manganese | 0.16 | 0.12 |
| Iron | 6.8 | 6.8 |
| Sulfur | 0.35 | 0.27 |
| Chlorine | 0.4 | 0.42 |
| Oxygen | 43.6 | 47.5 |
| Carbon | - | 4.3 |
| Sodium | - | 0.28 |
| unknown | 3.3 | - |

Table 1. Comparison between elemental content determined by Venera 14 and the laboratory Venusian simulant.

Gamma-ray spectra were obtained with a GSO detector, from reactions involving high energy neutrons (during the burst), thermal neutrons (shortly after the end of the burst), and delayed activation (after the accelerator was turned off). Studies were also performed to investigate the effect of the possible uncertain amount of the Venusian atmosphere that would contribute to the measurement. Other than for the expected additional contribution of carbon and oxygen gamma rays, no alteration in the spectra were observed. A presentation of the initial efforts on this work was given at the Vernadsky-Brown Microsymposium in Moscow in the Fall of 1993. A poster on this work was presented at the IAA meeting at the Johns Hopkins University Applied Physics Laboratory in April, 1994. A copy of the preprint for the IAA meeting is attached as Appendix 1.

## Fourier Transform Analysis of Germanium Spectra

A study has been initiated (with J. Arnold and A. Thakur - UC San Diego) to test the spectral analysis approach that was to be taken with the germanium detector spectra from Mars Observer.[4] As the satellite was between the Earth and Mars, it was desirable to test the adequacy of the code on realistic data. We realized that a realistic approximation of the spectra that were expected to be obtained by Mars Observer existed from data obtained with a Ge detector[5] in the German Continental Deep Drilling Project (KTB). The data consisted of gamma-ray spectra from prompt thermal capture and gamma-ray spectra from the decay of delayed radioactivities. Previous work had shown that the peak analysis results were in excellent agreement with data obtained in the laboratory from cuttings and core samples. In the current work, these spectra have been analyzed with a combination of a peak fitting program (GANYMED) and a Fourier transform analysis of the continuum. The results are very encouraging and we hope to compare these results with those obtained from a spline approach that has also been used to include the information in the Compton scattering response from a gamma-ray peak.

## References


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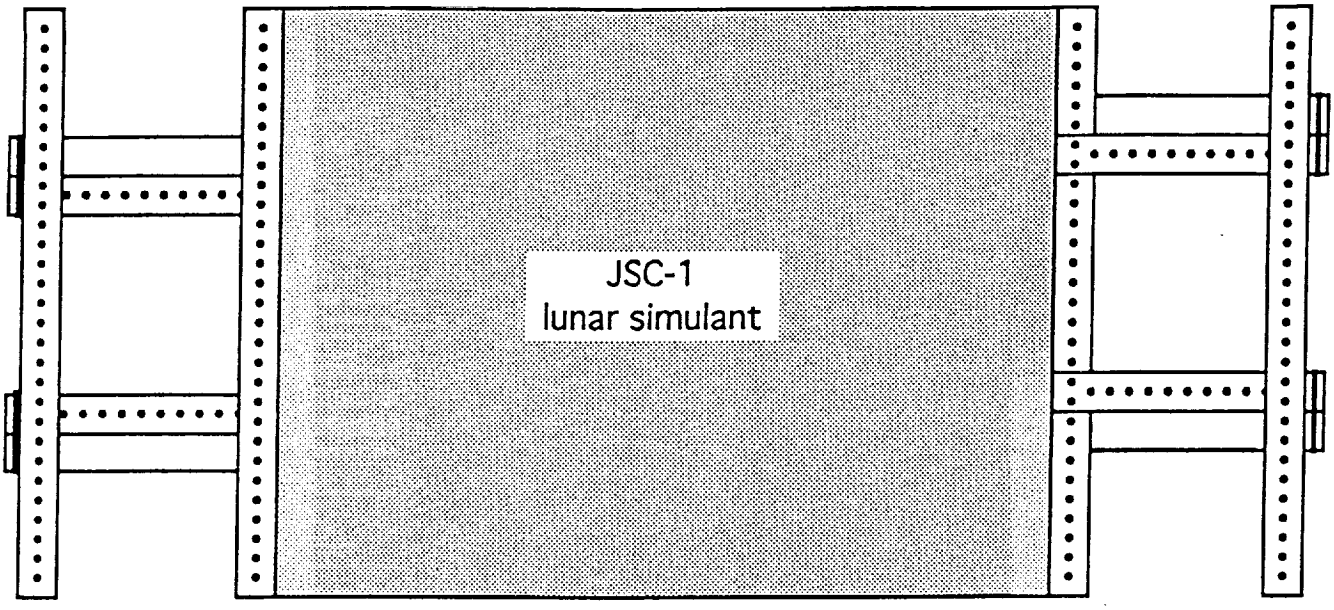
5) J.S. Schweitzer, C.A. Peterson, and J.K. Draxler. IEEE Trans. Nucl. Sci. **35**(1) 847 (1993).


## Figure Caption

Figure 1. Schematic of planetary detector calibration facility.

Detector Calibrator preliminary drawing

top view




side view

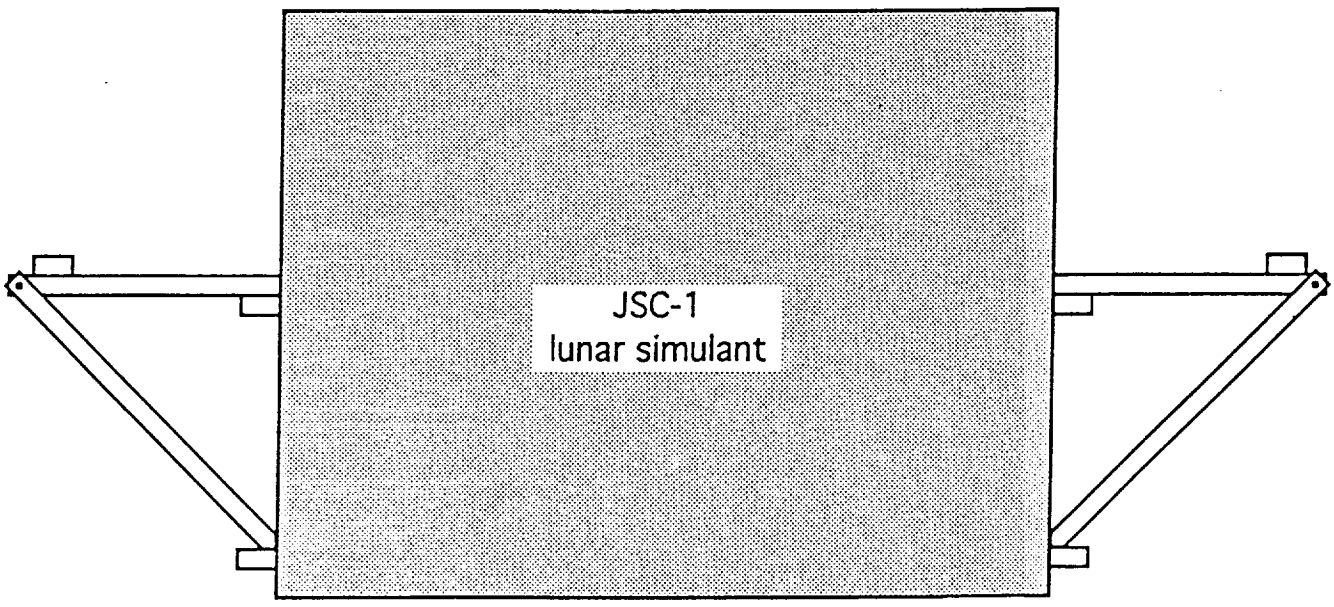



Figure 1

## Survey of Inorganic Scintillators

Although there are many substances known to scintillate under X- or γ-ray irradiation, the ideal scintillator for all applications does not exist, or at least has not yet been found. This ideal material would be:

- fast, similar to the fast component of $BaF_2$
- dense for a high γ-ray detection efficiency, as BGO
- high average Z, comparable to BGO
- high light output, such as NaI(Tl) or CsI(Tl)
- good spectral match of emission with a photocathode material, as NaI(Tl)
- no temperature dependence of the photon yield, as the fast component of $BaF_2$
- not hygroscopic
- rugged material
- inexpensive

In the absence of such a material the choice of a scintillator depends on the application and on the choice of the photon converter, i.e. the device which transforms the light of the scintillator into an electronic signal.

The present survey has been initiated to identify an optimized γ-ray detector to detect the γ-ray lines from elements. Thus, the interest is in a spectroscopic detector with as good an energy resolution as possible. The event rate is most often low and speed of the detector may only be sometimes an issue, but detection efficiency is. A high density and a large Z result in a smaller detector. Since the detector is often packaged in an anti-coincidence shield, a smaller detector's the savings in size and weight are amplified by the reduction of this shield.

## List of Inorganic Scintillators

Inorganic scintillators found in the literature are listed in table 1. Although this list is not complete, and there are many more scintillating crystals, most of them might be only interesting for special applications and do not promise to be better in the present search. Besides some well known crystals, there are many exotic materials in the list which are rarely used. From scanning the list, most materials can be easily rejected for this application, since the photon yield is rather low. Although the photon yield is not the only factor, a scintillator with a low light yield cannot provide the desired number of photons required for a good energy resolution. Other scintillators have too low a density or Z to be of interest here. Their efficiency is substantially lower than, for example, NaI(Tl) or BGO, a clear disadvantage for space applications.

The most common detectors presently used are NaI(Tl) and BGO. NaI(Tl) is currently the standard spectroscopy scintillator, but its density and Z are not very high. Therefore, BGO is often chosen where detection efficiency is more important than energy resolution, as for example in anti-coincidence shields. A reduction of candidates in the list is achieved by comparing the characteristics with NaI and BGO. A scintillator which does not have the potential to be better suited than either of the two is not worth considering in this context. In particular this means requiring that

either the photon yield is either comparable to or larger than NaI(Tl), or the density and Z are comparable to BGO and the photon yield is larger than the value for BGO. Preserving this artificial classification for the moment, table 2a lists the candidates which may show a better performance than NaI, and table 2b is the equivalent for BGO.

The number of candidates in table 2 is small. One group of interest are the rare earth oxyorthosilicates. Especially, LSO is interesting since the high density and Z provide a scintillator nearly as efficient as BGO, at least above 500 keV. Additionally, the light output is comparable to NaI(Tl), and the decay time is a factor of ten shorter. LSO could be a good spectroscopic detector which is more efficient than NaI(Tl), as well as a superior material for an anticoincidence shield, because of its better energy resolution and timing performance than BGO. These qualities are of special value for high energy gamma rays in order to recover the first and second escape peak.

The second group of interest are scintillators with emission in the red, namely CsI(Tl) and $CdWO_4$. Coupled either to red sensitive photocathodes or semiconductor photon converters like Si-diodes, an improved performance can be expected.

## Table 1: Inorganic Scintillators

| Crystal | Z | Density ($g/cm^3$) | Refractive Index | Hygro-scopic | Radiation Length (cm) | λ Fast Component (nm) | λ Slow Component (nm) | Decay Fast Comp (ns) | Decay SlowComp (ns) | Yield % NaI *a* | Light Yield (phot/MeV) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BGO | 75 | 7.13 | 2.19 | no | 1.11 | 480 | - | 300 | - | 13 | 8200 |
| BaCl2 | 50 | 3.90 | - | - | - | - | - | 1.2, 3.5 | - | - | 25000 |
| BaF2 | 53 | 4.88 | 1.49 | no | 2.06 | 220 | 310 | 0.60 | 620 | 5 *b* | 2200 *b* |
| BaI2 | 54 | 5.15 | - | no *c* | - | 190-340 | - | 6 | - | - | - |
| BaLiF3 | 51 | 5.24 | - | - | 2.13 | 240-440 | - | <25 | - | 5 | 2200 |
| BaYb2F8 | 63 | 6.99 | - | - | 1.3 | >310 | - | - | - | - | - |
| CaF2 | 17 | 3.19 | 1.44 | no | - | 435 | - | 940 | - | 40 | 24000 |
| CaWO4 | 67 | 6.12 | 1.92 | no | - | 430 | - | 500 | 20μs | 50 | 18000 |
| CdI2 | 52 | 5.67 | - | - | 1.5 | 540 | - | 3 | - | - | - |
| CdW04 | 65 | 7.90 | 2.2 - 2.3 | no | 1.06 | 540 | - | 5μs | - | 40 | 15300 |
| CeCl3 | 51 | 3.90 | - | - | - | - | - | 4.4, 23 | - | - | 28500 |
| CeF3 | 53 | 6.16 | 1.68 | no | 1.7 | 310 | 340 | 5 | 30 | 4 | 4000 |
| CeF3(Ca) | 53 | 6.10 | - | slightly | 1 | 340 | - | 30 | - | - | - |
| CsBr | 50 | 4.40 | - | no | - | 250 | 390 | .07 | >500 | 5 | 900 |
| CsCaCl3 | 47 | 2.90 | - | - | - | 205-305 | - | <1 | - | 10 | 5000 |
| CsCl | 52 | 4.00 | - | no | - | 240-270 | 390 | .88 | >500 | 5 | 900 |
| CsF | 53 | 4.11 | 1.48 | very | 2.0 | 390 | - | 2.80 | 4.40 | 5 | 2500 |
| CsI | 54 | 4.53 | 1.80 | slightly | 1.86 | 320 | > 400 | 10 | > 1μs | 4 | 2000 |
| CsI(Na) | 54 | 4.53 | 1.84 | yes | 1.86 | 420 | - | 630 | - | 75 | 39000 |
| CsI(Tl) | 54 | 4.53 | 1.80 | slightly | 1.86 | 565 | - | 1μs | - | 45 | 52000 |
| Gd2SiO5 | 59 | 6.71 | 1.85 | no | 1.38 | 440 | - | 56 | 600 | 25 | 10000 |
| KCaF3 | 17 | 3.00 | - | - | - | 140-190 | - | <2 | - | 5 | 2200 |
| KLuF4 | 63 | 4.80 | - | - | 2 | 165-200 | - | 1.5 | - | - | 170-400 |
| KMgF3 | 15 | 3.16 | - | - | 7.72 | 140-190 | 180 | 1.5 | - | 2 | 3500 |

*a* Relative Pulse Height with a Bialkali Photocathode
*b* Fast Component only
*c* Unstable in Air

| Crystal | Z | Density ($g/cm^3$) | Refractive Index | Hygro-scopic | Radiation Length (cm) | λ Fast Component (nm) | λ Slow Component (nm) | Decay Fast Comp (ns) | Decay SlowComp (ns) | Yield % NaI *a* | Light Yield (phot/MeV) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| KYF4(Rb) | 33 | 3.60 | - | - | - | 140-190 | - | 1.9 | - | 5 | 2200 |
| LSO | 66 | 7.40 | 1.82 | no | 1.14 | 420 | - | 12 | 42 | 75 | - |
| LXe | 54 | 3.06 | 1.5 | - | 2.77 | 170 | - | 3 - 25 | - | - | 26000 |
| LaF3(Ce) | 53 | >5.9 | 1.70 | - | - | 290, 305 | - | 3-27 | - | - | 2200 |
| LaF3(Nd) | 53 | 5.94 | 1.70 | no | - | 173, 245 | - | 6.3 | - | 5 | 200 |
| LiBaF3 | 51 | 4.90 | - | - | 2.3 | 200-230 | - | 1.9 | - | 5 | 2200 |
| LiI(Eu) | 52 | 4.08 | 1.96 | yes | - | 470 | - | 600 | 1.4µs | 35 | 11000 |
| LiYbF4 | 64 | 6.09 | - | - | 1.56 | 400-500 | - | <25 | - | 5 | 2200 |
| NaI(Tl) | 51 | 3.67 | 1.85 | yes | 2.6 | 415 | - | 230 | 1.5 ms | 100 | 38000 |
| PbCO3 | 76 | 6.6 | 1.80 | no | - | 475 | - | 5.6 | 27, 155 | <1 | - |
| RbCaF3 | 31 | 2.83 | - | - | - | - | - | 1 | - | 5 | 2200 |
| RbF | 35 | 3.60 | - | yes | - | 200, 380 | - | 1.3 | - | 5 | 2200 |
| ThF4 | 85 | 6.32 | - | - | 1.18 | 330, 450 | - | <25 | - | - | - |
| Y3Al5O12 | 33 | 4.56 | - | - | 3.5 | 550 | - | 65 | - | 12 | 14000 |
| YAlO3(Ce) | 33 | 5.55 | 1.94 | no | 2.63 | 350-390 | - | 17-35 | - | 30 | 18500 |
| YSO | 35 | 4.54 | - | - | - | 400 | 500 | 37 | 82 | 25 | - |
| ZnO | 29 | 5.61 | 2.02 | no | - | 385 | - | - | - | 40 | - |
| ZnS(Ag) | 28 | 4.09 | 2.35 | no | - | 450 | - | 200 | - | 150 | - |
| ZnWO4 | 64 | 7.84 | 2.20 | no | 1.12 | 475 | - | 5µs | 20µs | 26 | 9500 |

*a* Relative Pulse Height Measured with Bialkali Photocathode.

**Table 2a: Promising High Density Scintillators**

| Crystal | Z | Density ($g/cm^3$) | Refractive Index | Hygro-scopic | Radiation Length (cm) | λ Fast Component (nm) | λ Slow Component (nm) | Decay Fast Comp (ns) | Decay SlowComp (ns) | Yield % NaI *a* | Light Yield (phot/MeV) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BGO | 75 | 7.13 | 2.19 | no | 1.11 | 480 | - | 300 | - | 13 | 8200 |
| CaWO4 | 67 | 6.12 | 1.92 | no | - | 430 | - | 500 | 20μs | 50 | 18000 |
| CdW04 | 65 | 7.90 | 2.2 - 2.3 | no | 1.06 | 540 | - | 5μs | - | 40 | 15300 |
| Gd2SiO5 | 59 | 6.71 | 1.85 | no | 1.38 | 440 | - | 56 | 600 | 25 | 10000 |
| LSO | 66 | 7.40 | 1.5 | no | 1.14 | 420 | - | 12 | 42 | 75 | - |
| ZnWO4 | 64 | 7.84 | 2.20 | no | 1.12 | 475 | - | 5μs | 20μs | 26 | 9500 |

*a* Relative Pulse Height with a Bialkali Photocathode

**Table 2b: Promising Medium Density Scintillators**

| Crystal | Z | Density ($g/cm^3$) | Refractive Index | Hygro-scopic | Radiation Length (cm) | λ Fast Component (nm) | λ Slow Component (nm) | Decay Fast Comp (ns) | Decay SlowComp (ns) | Yield % NaI *a* | Light Yield (phot/MeV) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LSO | 66 | 7.40 | 1.82 | no | 1.14 | 420 | - | 12 | 42 | 75 | - |
| NaI(Tl) | 51 | 3.67 | 1.85 | yes | 2.6 | 415 | - | 230 | 1.5 ms | 100 | 38000 |
| YSO | 35 | 4.54 | - | - | - | 400 | 500 | 37 | 82 | 25 | - |
| CsI(Na) | 54 | 4.53 | 1.84 | yes | 1.86 | 420 | - | 630 | - | 75 | 39000 |
| CsI(Tl) | 54 | 4.53 | 1.80 | slightly | 1.86 | 565 | - | 1μs | - | 45 | 52000 |

*a* Relative Pulse Height Measured with Bialkali Photocathode.

## Compact PMTs

Schlumberger-EMR has a line of photomultipliers well suited to well logging applications in extremely harsh conditions. The expertise was developed and successfully applied Measurement-While-Drilling (MWD) operations, which subject the tool and detector to shock levels in excess of 500 g in a continuous fashion, and high levels of random vibrations. Problems arising from size limitations led to the development of compact PMTs with similar characteristics but a drastically reduced size. Tests conducted in 1993 for the qualification of this novel detector showed no performance degradation while allowing a smaller detector package. An added advantage was the development of extremely compact power supplies that use the volume around the electron multiplier structure. This development allowed operation of the detector to higher count rates than before, with higher reliability and linearity, while still reducing the original detector size.

The original size of a 1.25" diameter photomultiplier was 4.2" long. The compact PMT of the same diameter is 2.5" long when fully packaged with its biasing resistor network and the shock resistant potting. The integrated power supply brings the package to 3.1" length with no change in diameter. The power supply delivers up to 2400 V and operates up to 150°C, with a higher temperature version being finalized in the first half of 1994.

A similar approach is being applied to larger diameter ( 2" - 3" ) photomultipliers. A 3" photomultiplier can be packaged to a length of 3.5". This technology is being employed in the $\gamma$-ray detector for the NEAR project.

It is worth mentioning that these photomultipliers were developed for a large range of temperatures up to 200°C. The photocathodes are being matched to the various emission characteristics of the scintillating crystals, including, but not limited to, NaI(Tl), BGO, and GSO ( gadolinium oxyorthosilicate). Detectors including these scintillators are being successfully used in various applications.

## Short Term Plans

- **Microchannel Plate (MCP) PMTs**

  Replacing the multiplying structure in a PMT by a set of Multi Channel Plates could result in a significant length and weight reduction. MCP-PMTs provide an imaging capability which might considerably enhance the performance of present X-ray detection systems. Prototypes of such MCP-PMTs exist. The performance characteristics of these devices will be investigated.

- **Channel Electron Multiplier (CEM) PMTs**

  The main topic of this investigation is to determine if Channel Electron Multipliers can replace the classical PMT with an advantage in size, weight, or performance.

- **Other solid state electron multiplication devices**

  There are several possibilities to employ Avalanche Photo Diodes (APDs) to replace some parts of the multiplying structure in a classical PMT.

- **Miniature Detectors**

  Certain combinations of scintillating crystals, compact PMTs, and integrated power supplies offer unique characteristics of compactness, reliability, and performance for specific applications. The most promising combinations will be evaluated.

- **Space Qualification of Integrated Power Supplies**

  The miniaturized power supplies mentioned above have excellent characteristics of stability, ruggedness, and operating temperature range. When used with the small size PMTs they use the available space very efficiently and improve the high count rate linearity. They contain both passive and active surface mount components. The space worthiness of these power supplies will be evaluated.

# Appendix 1

# A NEUTRON ACTIVATION GAMMA RAY SPECTROMETER FOR PLANETARY SURFACE ANALYSIS

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## ABSTRACT

A pulsed DT neutron generator system, similar to that used in commercial well logging, offers the possibility of performing accurate elemental analyses to depths of tens of centimeters in a few seconds with the probe on the body's surface. Through time-phased measurements of the gamma-ray spectrum synchronized with the neutron pulses, concentrations of hydrogen, carbon and key mineral forming elements can be determined even with a low-resolution spectrometer. If a high resolution spectrometer is used, the number of elements measured and the sensitivity for measurement is increased. An implanted probe system, such as in a comet or ice cap penetrator, would offer the highest possible sensitivity.

An inexpensive neutron probe system based on modifications of the Schlumberger well-logging system has been proposed for the Discovery/Venera/SAGE Mission to Venus and the Mars Polar Pathfinder. Preliminary experiments on a simulated Venusian surface indicate that high quality results can be obtained.

## INTRODUCTION

There are a number of planned and contemplated NASA, ESA, and Russian solar system lander missions that will characterize planets and small bodies over the next ten years. These include missions to the Moon, Mars, Venus, asteroids and comets. Except for gamma-ray spectrometers, the existing suite of "demonstrated" instruments can only characterize the first fraction of a millimeter of the surface for elemental composition unless drilling or excavating techniques are used. Cosmic-ray induced activation analysis by gamma-ray counting can determine the composition of significant volumes, but only with tens of hours counting time for high quality measurements.

The new era of lower cost solar system exploration missions introduces constraints on the options for the science instrument systems. The selected science payload must always meet the resource constraints of the spacecraft and launch vehicle. The size and capabilities of the spacecraft and launch vehicle will most often be selected for their cost. It is also necessary to select the set of instruments that provides the optimum science return within the overall cost and resource constraints. This can mean only a few instruments are flown if expensive innovation is needed in the essential payload, or quality of science return may be sacrificed if existing instrument designs are used. However in some cases there are options for innovative instruments, use of existing designs for some instruments and space craft, and low cost implementation modes that can produce an exceptionally high value science return. This is the case with the proposed Discovery Venera Surface Atmospheric Geochemistry Experiment (SAGE) Mission.

The SAGE mission proposes that a select set of U.S. and Russian built instruments be flown on a Russian built Venus lander of the Vega design with a Russian provided launch vehicle. The proposed instrument set includes a new atmospheric chemical analyzer for descent operation, a surface imaging spectrometer for mineralogical identification, an Alpha Proton X-ray analyzer for elemental analysis of a retrieved sample, and the new Neutron Activation Gamma-Ray Spectrometer (NAGS) for analysis of the Venusian surface in-situ.[1] The APX and NAGS elemental analyzer systems are complementary. The APX system provides elemental analysis of a surface sample obtained by an external drilling system identical to that used on the Venera 13, 14 and Vega 1, 2 landers.[2] The drilling system can retrieve a sample of 1 to 6 $cm^3$ from the top few centimeters of the surface. The NAGS system on the other hand can provide an analysis of hundreds of $cm^3$ of the surface without the necessity for retrieving it. Thus a comparison of results can provide an indication of changes in chemistry in the first few centimeters depth due to atmospheric interaction. The APX experiment will determine the abundance of elements from C through Ni with concentrations greater than 1 to 5% by weight. The NAGS system will measure the abundances of H, C, O, Na, Al, Si, S, Ca, Ti, Fe, Gd+Sm, plus Cl and Mg (if present in appreciable quantities) by means of neutron inelastic scattering, capture, and delayed radioactivity. The sensitivity will be better than 0.1% in most cases, with Gd+Sm measured at ppm levels. In addition the natural radioactivities of K, Th and U will be measured at the site. The thick Venusian atmosphere prevents significant cosmic ray induced gamma-ray activation.

## INSTRUMENT SYSTEM

The NAGS instrument is based on the hardware and analytical principles developed by Schlumberger, Inc. for petroleum well logging. The instrumentation consists of a small deuterium-tritium neutron generator (DT minitron), its 80 kV high voltage power supply, a scintillator with a miniature, rugged ceramic photomultiplier tube and amplifier, and control electronics. Schlumberger has developed a number of configurations, but the most suitable one houses all components in lengths of 5.7 cm diameter cylinders that are interconnected and stacked for lowering into a bore hole. The commercial systems are engineered for continuous operation in very harsh down-hole conditions, up to 200° C, hundreds of Gs transient accelerations, and 20,000 $lb/in^2$ pressures (with steel housing). These basic components can readily be adapted to a number of planetary applications.

For the Venera/SAGE mission, the commercial system, with minor modifications, would be reconfigured and additionally packaged for the Venus surface environment so that it can be deployed from the lander. The instrument will be deployed to a distance of one to two meters by means of an arm that folds out from the side of the lander. The control and data acquisition electronics are divided between the deployed system and the lander. Measurements could be made with the NAGS system fixed at the bottom of the lander, however that position makes it particularly vulnerable to damage on landing, and it maximizes the neutron interaction with the lander, and thus decreases the sensitivity for the geochemical measurements. Deployment to one or two meters will decrease the gamma-ray signal from the spacecraft itself by one or two orders of magnitude.

The harsh Venusian environment, approximately 500 C and 100 atmospheres pressure at the surface, requires extraordinary thermal and mechanical designs for the lander and externally deployed instruments. Despite the inclusion of extensive thermal insulation and heat absorbers, the Venera and Vega landers are limited to, at most, two hours of surface operations. Preliminary analyses indicate that the NAGS system can be made to last two hours using the packaging system illustrated in Figure 1. The primary insulation is a metal vacuum dewar that completely

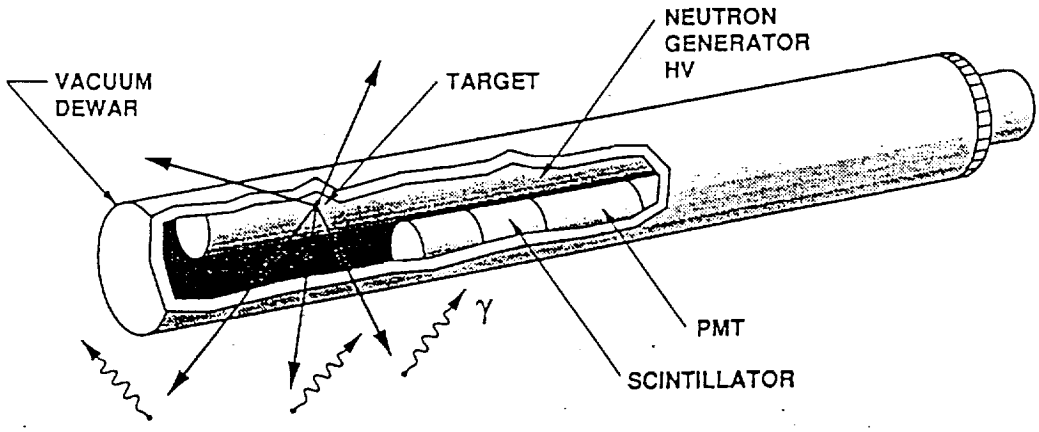


**Figure 1.** Schematic of packaging system for the NAGS in Venus environment

contains the neutron generator, spectrometer and electronics. Overall the dewar is about 1 meter long and 15 cm in outside diameter, 11 cm inside diameter. The vacuum wall contains high temperature multilayer insulation. The power and signal lines are carried through insulated connectors at one end. In order to limit the temperature rise rate, the voids within the inner dewar wall are filled with a heat absorbing phase-change material. Because the logging systems are mechanically and electrically designed for harsh deep-well conditions, no significant re-engineering of the generator and spectrometer systems is anticipated. The complete system would have a mass of about 27 kg including the thermal packaging. Approximately 30 W would be consumed to maximize neutron output for the operating period. This mass and power is well within the capability of a Vega lander to deliver and operate. For a less severe planetary environment, such as Mars, the neutron probe system mass and power requirement by would be less by, perhaps, an order of magnitude.

In well logging applications the neutron generator and gamma spectrometer systems are in one linear string with neutron scattering material between the them to minimize line-of-sight neutron interaction. However a completely in-line system would be too long to be accommodated on a Venera/Vega lander. Thus the neutron generator with its power supply are placed beside the spectrometer system with the scattering material close to the scintillator. This is still excellent geometry.

Clearly there are important similarities and differences between using the NAGS system in a petroleum well and on the surface of a planet, Venus in particular. In both cases, the system must be mechanically and electrically rugged. In both cases the system must produce high quality spectral data under extreme mechanical stress and rapid temperature changes. The ability to perform well under these conditions is fundamental to the existing commercial logging systems.

The two most important differences between well logging and the planetary system are the geometry and the amounts of neutron moderator present. In a well logging application, the neutrons are interacting with rock that is nominally in $4\pi$ geometry around the source and detector, whereas in the case of the surface location, the material to be analyzed is only in one hemisphere. This has the effect of decreasing the overall sensitivity of measurements because approximately half the neutrons will never interact with the solid surface, and additional neutrons will be scattered out of the solid before they are captured.

The second major difference from well logging is the relative amounts of neutron moderator present. In well-logging applications the generator is always surrounded by significant concentrations of hydrogen-containing fluids such as water and hydrocarbons. These act to very efficiently slow down the neutrons so that they are captured within a few tens of centimeters from the generator. Thus the gamma ray signal from neutron capture is strong in a scintillator close to the generator. On the other hand, on Venus or other "dry" planets there is little or no hydrogen present so that the neutrons may travel several times farther before they are captured. Thus the optimum capture signal may be obtained farther from the generator.

Data Acquisition

The data acquisition strategy as been well developed for the well logging applications, and an essentially similar strategy is used for a planetary application.[3] The gamma-ray signal at the spectrometer detector contains components from neutron inelastic scattering, neutron capture, and delayed radioactive decay. The separation of these components can enhance the sensitivity for some elements. Although the gamma ray spectrum from each element is unique, when the spectrum is derived from a relatively low resolution detector, such as the scintillator system, the lines are not uniquely resolved and separation of components is a considerable advantage. Thus the strategy is to measure the gamma rays as a function of time following a microsecond burst of neutrons. The inelastic scattering of the primary 14 MeV neutrons, (n,n') reactions, results in immediate emission of gammas from the excited nuclei. The capture of the neutrons by target nuclei, $(n,\gamma)$ reactions, results in prompt emission of gamma rays, but there is a delay of some microseconds between emission of the primary neutrons and the capture because capture is more

likely for slow neutrons. The emission of gammas by decay of activated nuclei is statistically delayed by the half life of the nucleus.

A typical data acquisition scenario is as follows. The neutron generator is pulsed on for about 10 microseconds every millisecond. A "pulse gate" gamma spectrum is accumulated during the pulse. This spectrum is dominated by (n,n') reactions. Then a "capture" spectrum is accumulated for a few hundred microseconds. This spectrum is dominated by the (n,γ) reactions. Then, perhaps with some hundreds of microsecond delay, the "delay activation" spectrum is accumulated for a few hundred microseconds. This spectrum is dominated by decay of radioactive nuclei. The intercomparison of these spectra, and subtraction of various components allows analysis for H, C, O, Na, Al, Si, S, Ca, Ti, Fe, Gd+Sm, plus Cl and Mg (if present in appreciable quantities) with sensitivities of better than 0.1% for most components and Gd+Sm with ppm sensitivities. The quantitation process has been described elsewhere.[4,5]

## EXPERIMENTAL TESTS

A number of laboratory experiments were performed to investigate the quality of the spectra that could be obtained on the Venusian surface by a neutron generator (output > $10^8$ n/sec) with a 3.5 cm diameter x 7.5 cm cerium-doped gadolinium oxyorthosilicate (GSO) gamma-ray detector. Simulations of the Venusian surface were made in a 68 cm x 99 cm x 75 cm polyethylene container. Initial measurements were made with a $CaCO_3$-filled or $SiO_2$-filled container. These measurements were intended to evaluate the effects of the $CO_2$ atmosphere on the shape of the spectra and to "salt" the formation with individual elemental compounds to evaluate the spectral shapes for each individual element. Subsequently, a simulation of the Venusian surface was constructed to provide a close approximation of the elemental content from the results obtained by Venera 14.[6] The elemental content of the resultant simulation is compared with the Venera 14 results in Table 1.

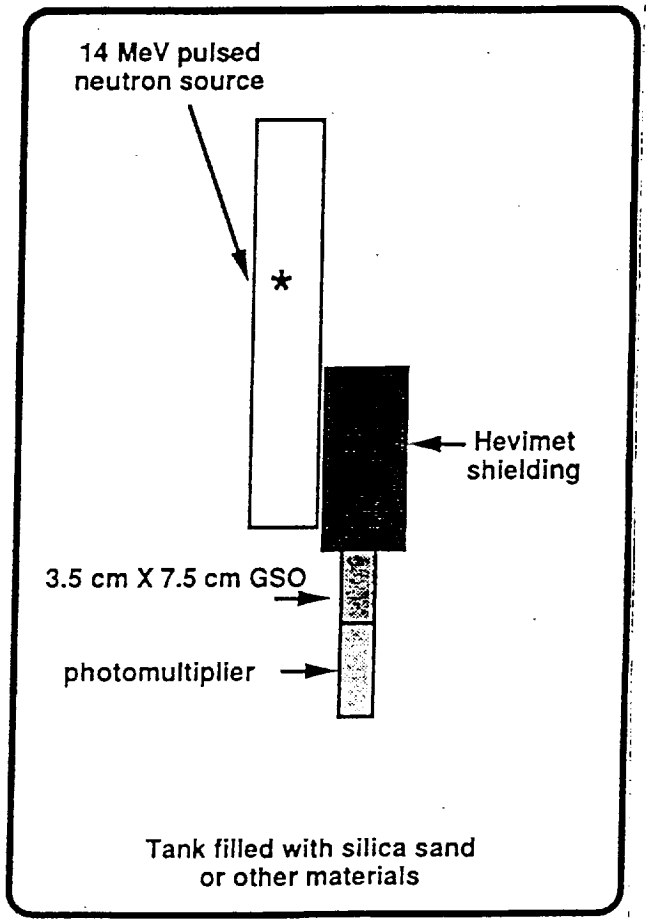


**Figure 2.** Schematic drawing of the top view of the laboratory experimental setup.

All measurements were performed with the neutron generator, shielding, and the detector-photomultiplier combination lying on the surface of the formation, as shown schematically in Figure 2. Since the Venusian environment is characterized by being essentially hydrogen free, the

slowing down and diffusion properties of neutrons are controlled by the other light elements present, rather than hydrogen as is usually the case on Earth. As there is uncertainty on how much of the $CO_2$ atmosphere may permeate the Venusian soil and on whether there will be a portion of the atmosphere between the neutron generator and the detector and the soil being measured, we attempted to evaluate the effect of the variation of neutron moderation properties on detected gamma-ray spectral shapes by comparing simple spectra obtained with and without substantial $CO_2$ present. Spectra were obtained by placing the neutron generator and detector directly on the $SiO_2$ soil surface and by repeating the measurement with a 5 cm layer of solid $CO_2$ between the neutron generator and detector and the soil surface.

To provide an estimate of the spectral shape for individual elements, packages, containing typically 1 kg of individual element oxides or carbonates, were placed about 10 cm beneath the $CaCO_3$ soil surface between the neutron generator and the GSO detector. The resulting spectra will provide individual spectral response functions after subtracting the contribution from the common $CaCO_3$ content.

**Table 1.** Comparison between elemental content determined by Venera 14 and the laboratory Venusian simulant.

| Element | Venera 14 Measurements (wt percent) | Venusian Simulant (wt percent) |
|---|---|---|
| Magnesium | 4.9 | 4.3 |
| Aluminum | 9.5 | 7.9 |
| Silicon | 22.7 | 19.5 |
| Potassium | 0.17 | 0.65 |
| Calcium | 7.4 | 7.2 |
| Titanium | 0.75 | 0.75 |
| Manganese | 0.16 | 0.12 |
| Iron | 6.8 | 6.8 |
| Sulfur | 0.35 | 0.27 |
| Chlorine | 0.4 | 0.42 |
| Oxygen | 43.6 | 47.5 |
| Carbon | - | 4.3 |
| Sodium | - | 0.28 |
| Unknown | 3.3 | - |

All electronics for processing the detector outputs used standard laboratory electronics. Spectra to reflect the fast neutron-induced gamma rays, those due to thermal neutron capture reactions, as well as the spectrum of gamma rays from the decay of delayed radioactivity were obtained by gating the detector electronics with signals from the pulse from the neutron generator.

## RESULTS

The test of the effect of the $CO_2$ atmosphere can be seen in the capture spectra shown in Figure 3. If there were significant changes introduced by the $CO_2$ atmosphere, then a change in

the peak height to scattered background would be expected. The figure shows the gross thermal neutron capture gamma-ray spectrum without any $CO_2$ present (dashed curve) with the corresponding spectrum obtained with the 5 cm of $CO_2$ between the equipment and the formation surface (solid curve). The only significant change in the spectral shape is from the additional oxygen activation photopeaks (the triplet at roughly 6, 5.5 and 5 MeV) and the Compton background to lower energies from these peaks. In the region of the silicon thermal neutron capture gamma-rays, there is no significant change in the peak or background portion of the spectrum when the solid $CO_2$ is introduced. Thus the shape of the gamma-ray standards are expected to be minimally perturbed by the exact amount of $CO_2$ atmosphere present during the measurement, indicating that this factor would probably not be an important limit on the accuracy of derived elemental concentrations.

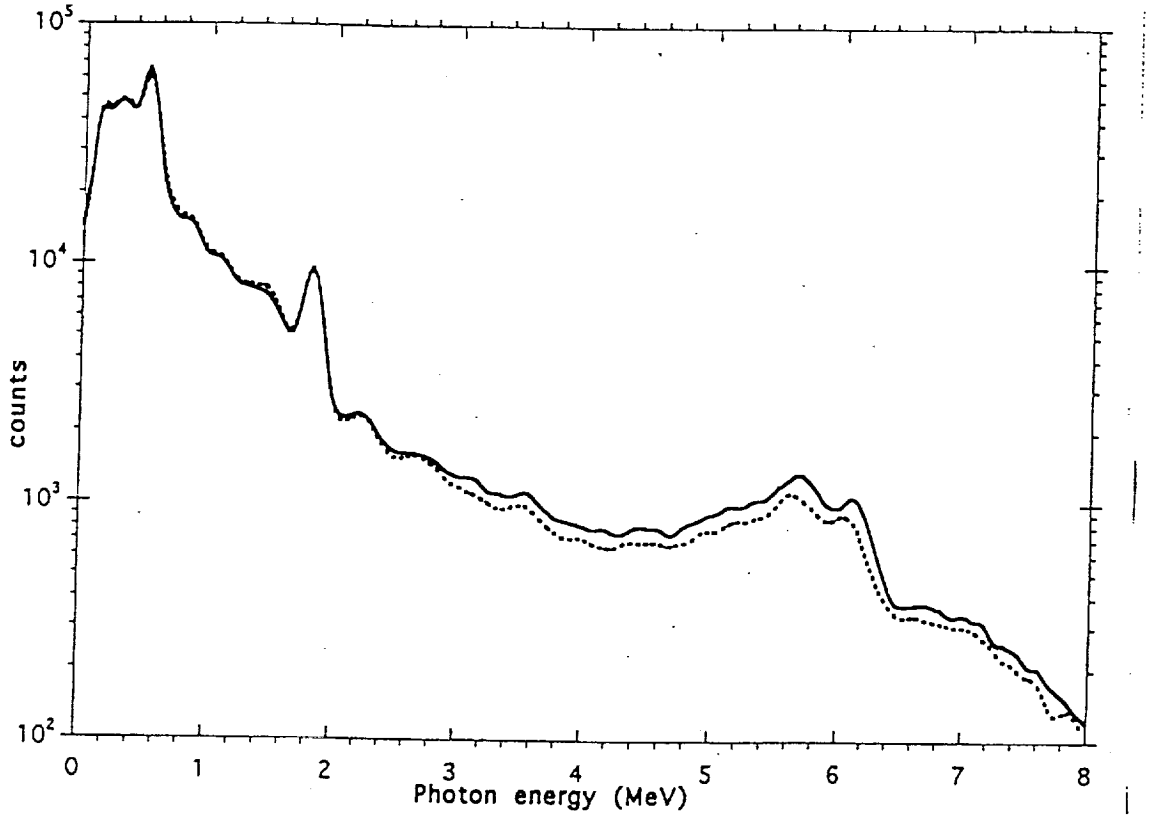


**Figure 3.** Comparison between thermal neutron capture gamma-ray spectra obtained on a quartz formation with (solid curve) and without (dashed curve) $CO_2$ between the surface and the instrument.

Two typical neutron capture gamma-ray spectra are shown in Figures 4 and 5 where $TiO_2$ and $Fe_2O_3$ are salted in the $CaCO_3$ matrix. In both cases the contributions from the added elements can be clearly identified. These spectra confirm that elemental standards could be derived for the response of the spectrometer to individual elements contained in the measurement volume.

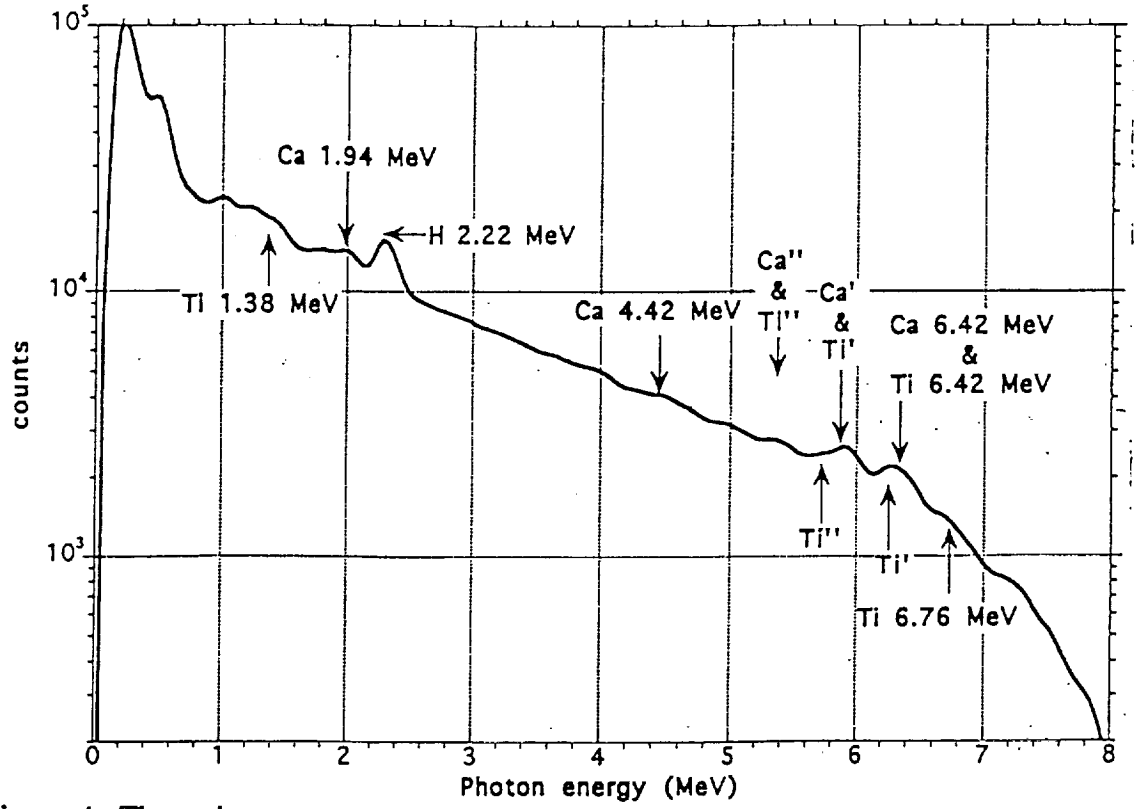


**Figure 4.** Thermal neutron capture gamma-ray spectrum when the calcite simulation is "salted" with $TiO_2$.

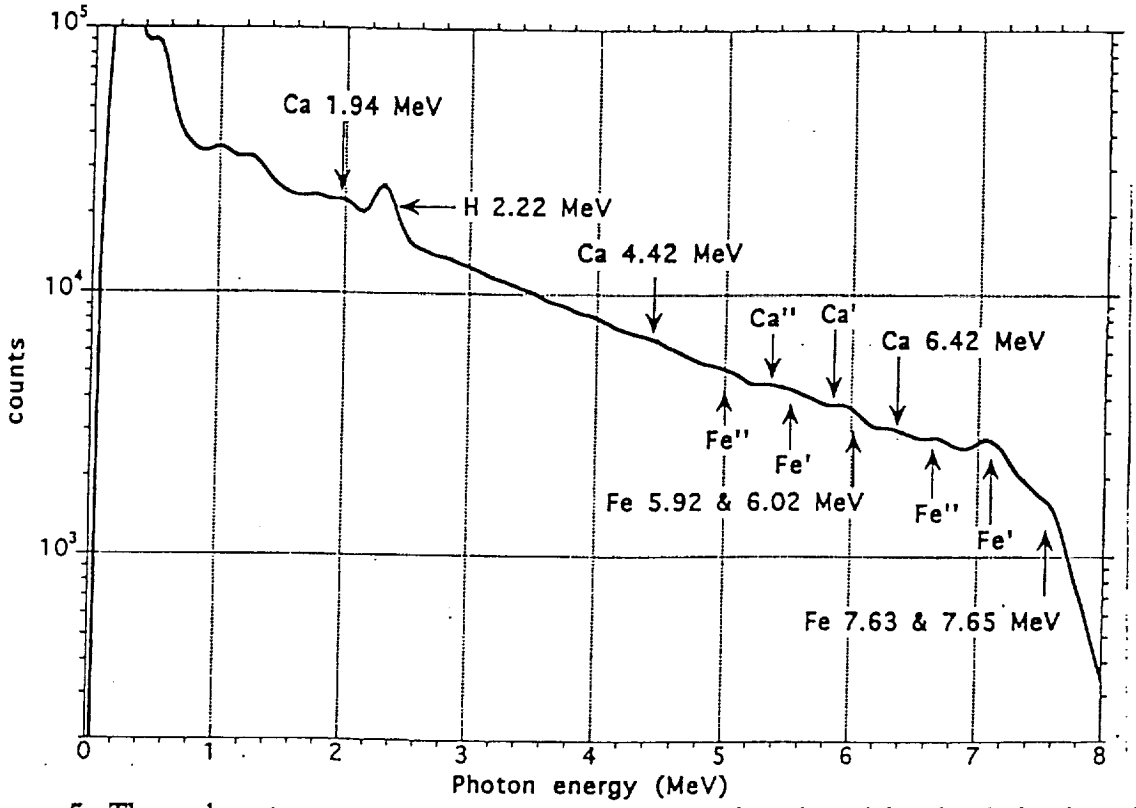


**Figure 5.** Thermal neutron capture gamma-ray spectrum when the calcite simulation is "salted" with $Fe_2O_3$.

Figure 6 shows a thermal neutron gamma-ray capture spectrum obtained with boron surrounding the detector to minimize the spectral contribution from the detector package. This spectrum was obtained in the complete simulation, whose elemental content is shown in Table 1. Numerous peaks can be identified from the elements in the simulation, indicating that these elements, as well as perhaps some of the others whose peaks are not visually obvious, can be quantitatively determined. It should be noted, of course, that some of the elements would be determined from prompt neutron-induced reactions, such as carbon, oxygen, and magnesium, and from delayed radioactivity, such as aluminum, manganese, and sodium.

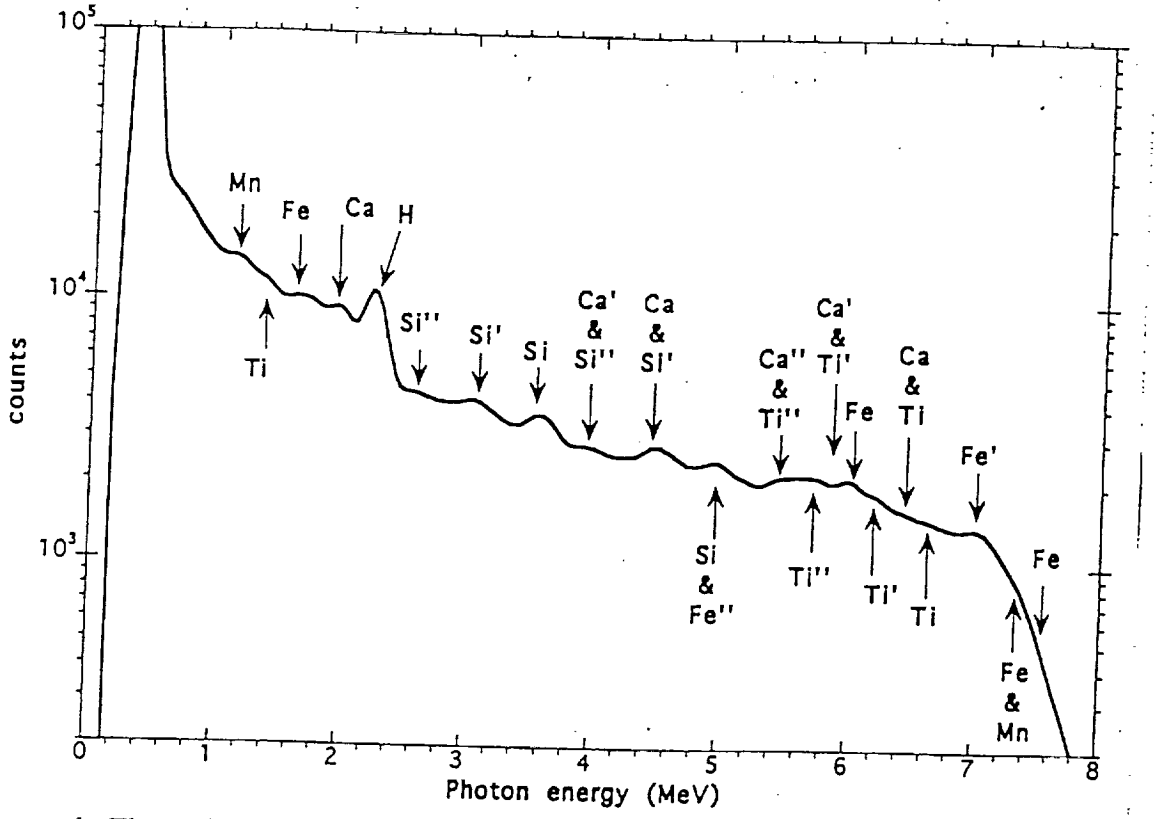


**Figure 6.** Thermal neutron capture gamma-ray spectrum in the complete simulant model whose composition is given in Table 1. The hydrogen peak is from the environment surrounding the simulant.

## DISCUSSION

The technique of using a gamma-ray detector together with a pulsed neutron generator to determine accurate elemental abundances has been well developed for remote sensing applications on Earth in rugged environments. Such systems can be applied to non-orbital planetary environments to provide elemental concentrations of the surface constituents averaged over the first tens of centimeters in depth. In an impact scenario a volume of tens of centimeters in radius around the probe location can be analyzed. The particular choice of system components for planetary missions is governed by the particular mission environment. The selection of GSO for the Venusian measurement is based on its properties at elevated temperatures[7] where it can maintain a good light output with an acceptably fast scintillation light decay constant over the

entire range of anticipated measurement temperatures. In addition, it provides a good volumetric detection efficiency, minimizing the size of the dewar while maintaining a good gamma-ray spectral response. For a colder environment, a better choice might be cerium-doped lutetium oxyorthosilicate[8] which has a faster decay time, essentially the same volumetric detection efficiency as BGO and has essentially constant output and time characteristics between 11 K and room temperature, providing better spectral stability and easier electronics design. Of course, in situations where no neutron generator is provided (i.e., using cosmic rays to induce the reaction gamma rays) other detectors such as BGO may be more than adequate. When extensive multielement analysis is required, a neutron generator can be coupled with a germanium detector for optimum energy resolution and detection sensitivity.

The data presented here are not sufficient for making accurate predictions of anticipated statistical uncertainties or minimum detection limits for the Venera measurement. However, experience has indicated that when even a hint of spectral peaks can be seen in the measured spectrum acceptable precision can be obtained for the elements that make a reasonable spectral contribution to the measurement. In fact, it is possible to quantify elemental concentrations at reasonable levels of precision even when there is no visual indication of specific peaks. Laboratory measurements can be used to predict quantitatively the performance of such a system under a particular planetary measurement environment[9], but resources were not available to perform the complete study here.

These measurements do confirm, however, that the use of a gamma-ray detector with pulsed neutron generator in the Venusian environment can perform a significant elemental analysis to provide greater insight into the nature of the surface rocks on the planet. The application of this technique to planetary environments with significantly different surface constituents, such as comets, is currently being evaluated.

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**13. ABSTRACT** *(Maximum 200 words)*

Detectors that will be used for planetary missions must have their responses calibrated in a reproducible manner. A calibration facility is being constructed at Schlumberger-Doll Research for Gamma- and X-ray detectors. With this facility the detector response can be determined in an invariant and reproducible fashion. Initial use of the facility is expected for the MARS94 detectors.

Work is continuing to better understand the rate Earth oxyorthosilicates and to define their characteristics. This will allow a better use of these scintillators for planetary missions. In a survey of scintillating materials, two scintillators were identified as promising candidates besides GSO, LSO, and YSO. These are CdW04 and CsI(T1). It will be investigated, if a detector with a better overall performance can be assembled with various photon converters.

Considerable progress was achieved in photomultiplier design. The length of an 1" diameter PMT could be reduced from 4.2" to 2.5" without performance degradation. This technology is being employed in the gamma-ray detector for the NEAR project. A further weight and size reduction of the detector package can be achieved with miniaturized integrated power supplies.

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