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TITLE: **GERMANIUM GAMMA-RAY SPECTROMETER PGS FOR THE MARS-96 MISSION**

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Germanium gamma-ray spectrometer PGS for the MARS-96 mission

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ABSTRACT

The Precision Gamma-ray Spectrometer (PGS) on the Russian MARS-96 spacecraft is designed to measure 0.1-8 MeV gamma rays in order to determine the elemental composition of the Martian surface, to study solar flares, and to determine energy spectra and times of arrival of gamma-ray bursts. The PGS instrument contains two high-purity, n-type germanium crystals, each similar to the one used on the Mars Observer mission. Each crystal is contained in a titanium can with Helicoflex cryogenic metal seals. An annealing capability allows repair of radiation damage. The detectors are cooled via nitrogen heat pipes attached to a passive radiator mounted on the back side of a solar panel. The radiators are designed to keep the Ge detectors below 100 K during the interplanetary flight. The electronics include first-stage electronics mounted on each crystal can and 4096-channel pulse height analyzers. Two parallel channels of electronics are provided and can be cross-switched by telecommands. In November 1995 integration of the flight detectors with flight electronics and testing of the complete system cooled by the passive radiator were successfully completed. The energy resolution degrades to about 3 keV in the flight configuration. Warming the radiators indicated that for the worst case when the radiator views Mars at the equator the maximum temperature of the detectors will be limited by the diode action of the heat pipes to 118 K. Extensive calibrations with radioactive sources are in progress. We conclude that we have an improved design for planetary and gamma-ray burst studies and the PGS instrument is ready for launch in November 1996.

Keywords: Mars, gamma-ray detector, spectrometer, remote sensing, planetary, gamma-ray burst, solar flares

1. Introduction

MARS-96 is a Russian planetary mission scheduled for a Proton launch from the Baikonur cosmodrome in November 1996. The MARS-96 spacecraft is a three-axis-stabilized spacecraft similar to the two used for the Phobos mission in 1988-1989 but with modifications based on the experience during the Phobos mission. MARS-96 will arrive at Mars in late 1997 and have a nominal lifetime of 2.5 years in a 43-hour elliptical polar orbit around Mars with a pericenter altitude above Mars of about 300 km. The primary objective of the MARS-96 mission is planetary studies of Mars, including the surface and atmosphere. Some instruments, including PGS, will be on the orbiter for global studies of Mars, and some will be on landers or penetrators for detailed studies of selected regions of the Martian surface.[1] PGS and other scientific instruments will collect data during cruise to Mars and during most of each orbit (except close to pericenter) for astrophysical and solar studies, secondary objectives of the MARS-96 mission.

Several gamma-ray spectrometers (GRS) are scheduled to fly on the MARS-96 spacecraft for orbital measurements. The PHOTON GRS consists of two detectors, both using cesium iodide (CsI) scintillators with about 7.5% energy resolution at 662 keV. One crystal is inside a bismuth germanate collimator mounted on a steerable platform to perform high-spatial-resolution measurements. The other is a large uncollimated CsI crystal on a solar panel to get better counting statistics of Martian gamma rays. The Gamma-Ray Burst Monitor (GRBM) is a small CsI crystal to measure with good time resolution x rays and low-energy gamma rays expected from gamma-ray bursts. GRBM shares some electronics with PGS.

PGS, the high precision gamma-ray spectrometer, which is the subject of the present report, contains two high-purity n-type germanium (Ge) detectors, each similar to the one used on the Mars Observer mission,[2] and is mounted on the back of a solar panel (Fig. 1). Although the PGS has less efficiency for detecting gamma rays than the PHOTON GRS and for detecting low-energy gamma rays than GRBM, its very high energy resolution (~3 keV at 1.3 MeV) enables it to resolve many gamma-ray lines from the Martian surface, cosmic gamma-ray bursts, and solar flares in the energy range from 0.1 to 8 MeV, and down to ~50 keV with reduced efficiency, in 4096 energy channels.

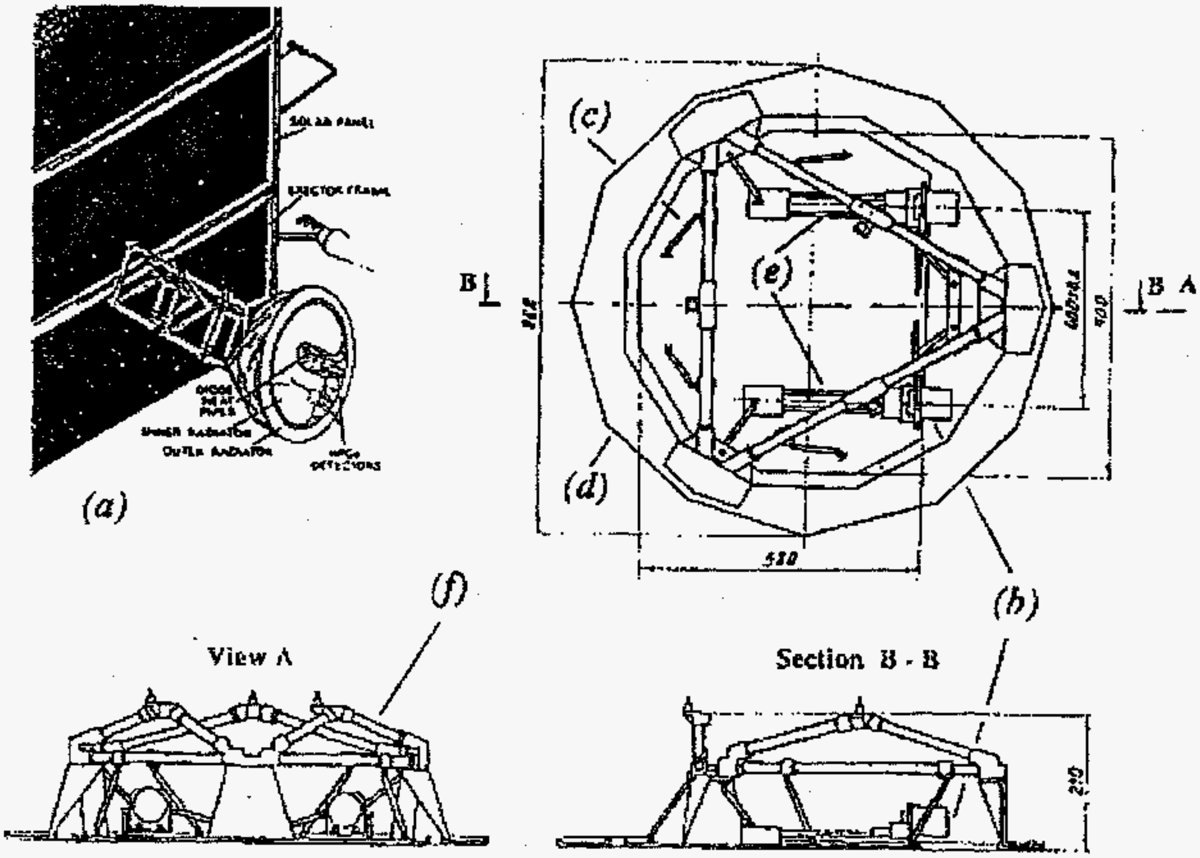


Fig. 1. a) Coolers and detectors deployed on the back of the solar panel. b) Detectors. c) Inner radiator. d) Outer radiator. e) Heat pipes. f) Thermally resistant supporters. The structure is shown without multi-layer insulation and the dimensions are in millimeters.

The primary objective of the PGS and PHOTON spectrometers is to map the Martian surface's elemental composition using the nuclear gamma lines. The major gamma rays used to map elemental abundances are those made by the decay of naturally-occurring long-lived radionuclides and by cosmic-ray-produced gamma rays made by $(n,n'\gamma)$ and (n,γ) reactions at depths down to tens of centimeters in the surface. Analysis of such gamma-ray data has been discussed for APOLLO and other missions.[3-7]

PGS will be the first instrument to give a global, high-energy-resolution, gamma-ray map of a planetary body, if successful. Previous instruments include the APOLLO spectrometers based on NaI(Tl) scintillators used to map 22% of the Moon's surface,[8] the scintillator-based spectrometers on the Russian missions MARS-5 and PHOBOS-2, which produced very limited data,[9-12] and the germanium detector on Mars Observer mission,[2] which failed three days before insertion into orbit around Mars.

The PGS is a joint collaboration of the Institute of Space Research (IKI) in Moscow and the Los Alamos National Laboratory (LANL) in Los Alamos, New Mexico. IKI is providing the passive cooler for the detectors, the low- and high-voltage supplies, the pulse height analyzers, and the data processing units. The detectors and cooler will be mounted behind a solar panel on a Russian designed and built deployment mechanism (Fig. 1). LANL is providing the two high-purity Ge detectors and the analog electronics. The mission was originally planned to launch in 1994 as MARS-94, and the delay has allowed additional improvements and testing of PGS. The present report describes some of this recent work; the earlier work is discussed in previous reports.[13-15]

2. Detectors

Each detector contains a single n-type crystal in a closed-end coaxial configuration. The specifications of the detectors as received from Princeton Gamma-Tech, Inc., before installation of the flight first-stage electronics are listed in Table 1.

Table 1. Detector specifications

Serial Number	2596	2600	2570
Assignment	flight	flight	spare
Diameter (mm)	56	56	56.7
Length (mm)	56.5	56.5	56.7
Active volume (cm^3)	130	130	135
Relative efficiency (%)	26.2	29.2	32.4
Peak/Compton	53.1	55.7	67.9
Energy resolution (keV)			
At 1332 keV	1.81	1.76	1.83
At 122 keV	0.960	0.880	0.810

The relative efficiency is the ratio of the photopeak area seen by the germanium detector to the photopeak area seen by a 7.62 cm (dia) x 7.62 cm (length) NaI(Tl) detector when a ^{60}Co source is placed 25 cm from the front surface of the crystal and on axis. The energy resolution quoted here is for an optimized laboratory setup, and more realistic results with flight electronics in noisy environments are discussed in Section 4.

The encapsulation of the crystals in metal cans is similar to that used for Mars Observer but with one very important difference. The sizes of the crystals were selected so that the same size cans could be used by just adjusting the thickness of thin Teflon electrical insulating liner between the crystal, which is biased at about -2800 V, and the can at ground potential. The wavy spring pushing the crystal against the bottom of the can, the circular insulators, and the electrodes are identical. What is different is the vacuum seal. The flight Mars Observer detector used a titanium can with indium seals, and the non-flight Mars Observer detectors used aluminum cans with indium seals. Early in our program when we were building hardware for MARS-94 we tried to use aluminum cans with indium seals. These encapsulated crystals are placed in cryostats under vacuum for testing. We discovered that the detectors operated nominally at first at liquid nitrogen temperature but began to break down under high voltage after one or more thermal cycles in which the detector was warmed to room temperature, the cryostat was vented with nitrogen gas to atmospheric pressure so that flight hardware could be installed, the cryostat evacuated to a vacuum of 10^{-5} torr, and the detector cooled again to liquid nitrogen temperature. We determined that the indium seals began leaking after this cycling. Of course, if the cryostats remain under vacuum, as is normal for unencapsulated laboratory germanium detectors, no leaking occurs and the detectors continue to operate nominally.

We solved the problem for MARS-96 by redesigning the encapsulation after the launch was delayed until 1996. First, we switched the material from aluminum to titanium because titanium provides some gettering to supplement the pumping action of the zeolite in the small capsule inside the can and because the titanium can was successful on the Mars Observer flight detector. Second, we modified all sealing surfaces to accept Helicoflex cryogenic metal seals, which have a leak rate of $<10^{-13}$ atm·cm^3/s in the operating range -272 to 700°C. Helicoflex seals are being used successfully on the Monitoring X-ray Experiment (MOXE) to contain helium[16] and were considered for another space germanium detector, the Transient

Gamma-Ray Spectrometer (TGRS) on the WIND mission,[17] until it was decided to use an aluminum can, which is too soft for these seals. We have had no problems with leaking and high-voltage breakdown since we switched to these seals.

Each detector has a heater to anneal radiation damage in the germanium crystal caused by galactic cosmic rays. Experience with the Mars Observer GRS and simulations at accelerators[18] show that the Ge detectors in one year, the time from launch to Martian orbit, will suffer enough radiation damage that the resolution will be degraded from the nominal 3 keV to ~6 keV. The radiation produces traps for the electrons and holes, thus delaying charge collection and causing long low-energy tails, which are difficult to analyze with standard peak-fitting codes and result in increased statistical uncertainties.

Annealing is planned after several months of data collection in orbit about Mars. After power is first applied to the heater, a wax actuator will puncture a hole in a thin titanium membrane at about 60°C to vent any possible outgassing to space. Annealing of the radiation damage will require 1-3 days at ~100°C and will be limited to avoid excessive diffusion of the lithium in the n^+ contact.

In the original design a 10-W heater with an area of 6.45 cm^2 was just attached to the outside of the can with adhesive supplied by the manufacturer. The heater worked fine in tests when full power was suddenly applied at room temperature but overheated when the starting temperature was ~100 K. We attribute this to the fact that the contact provided by the adhesive was not adequate and the relatively poor conduction of the thin wall titanium can created hot spots. Our present design uses a larger area 10-W heater, 12.90 cm^2, and a separate aluminum mounting to which the heater is attached with space-qualified epoxy. The aluminum mounting is attached to the detector with the four screws that mount the detector to the cooler. Tests indicate no evidence of overheating, and the heat supplied to the detector is adequate for annealing.

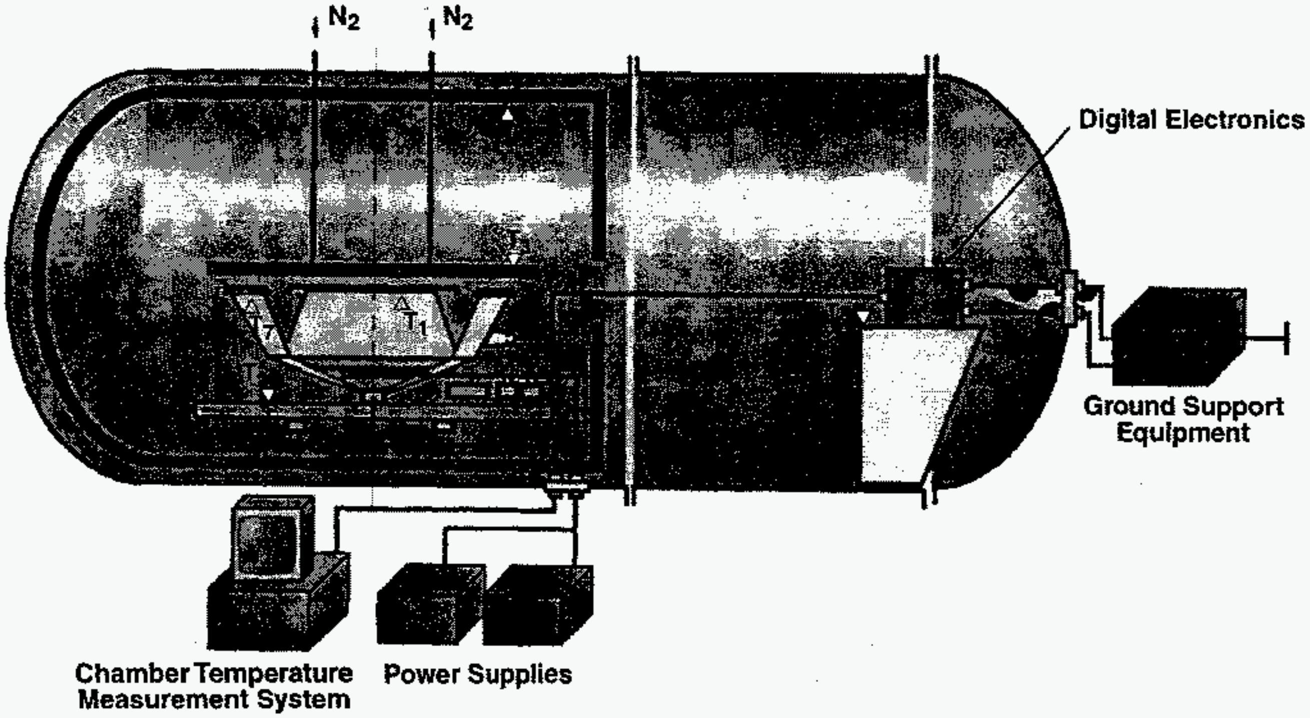
3. ELECTRONICS

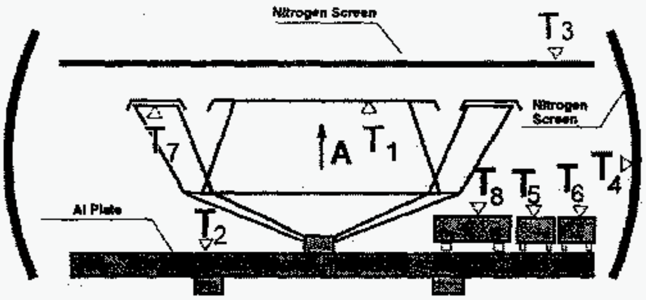
Instrument electronics include first-stage analog electronics, mounted on each crystal can; power converters, providing low voltages and the high voltages biasing the sensors; and digital processing and control electronics. The analog electronics, containing preamplifiers and shaping amplifiers and collectively designated SpAmp, are contained within a single housing that is mounted on the deploying platform directly beneath the thermal radiators and relatively near the sensors. Each SpAmp produces pulses of 0-8 volts for 0-8 MeV deposited in the crystal. The power converters are mounted on the solar panel, near the base of the deploying platform. Digital electronics, including two 4096-channel pulse height analyzers based on successive approximation ADCs, are located on the body of the spacecraft. Two parallel channels of electronics are provided and can be cross-switched by telecommands.

4. THERMAL VACUUM TESTING

The detectors need to operate below ≈130 K, and colder is better to minimize the degradation of the resolution due to radiation damage of the crystal.[18] The detectors are cooled via heat pipes attached to a two-stage passive radiator. The radiators have a thermally-tuned white coating that cools by radiating to space and are designed to keep the Ge detectors below 100 K during the interplanetary flight. The PGS is on the back of a solar panel about 70 cm from the spacecraft (Fig. 1), which insures that the radiators do not see the Sun. After launch, the radiators are extended from the solar panel and tilted so that they do not see any part of the spacecraft. Each Ge detector will be coupled to the inner radiator with two stainless-steel/nitrogen diode heat pipes that allow heat from the detector to easily flow to the radiator but strongly hinder heat flow from the radiator to the detector. An early test in a thermal vacuum chamber using a prototype cooler and dummy detectors indicated that the detectors should cool below 100 K, should not rise above ≈120 K in the worst case of Martian albedo falling on the radiators, and recover after the rise within 14 hours.[14]

The most recent test, which occurred in June 1996 and used the flight detectors integrated on the flight cooler, provided better data. The setup is shown in Fig. 2. The cooler with the detectors was supported by an aluminum plate but thermally decoupled from it by the highly resistant support structure of the cooler and the thermal blankets on the back of the cooler. The SpAmp amplifier, high-voltage power supply, and GRBM were supported and thermally coupled to the aluminum, whose temperature was controlled with electric heaters to simulate the temperatures these units will experience





Locations of the Temperature Monitors for PGS

Fig. 2. Thermal vacuum chamber used to test the PGS instrument. T_1 - inner radiator, T_2 - Al plate, T_3 - pumped nitrogen screen, T_4 - outer nitrogen screen, T_5 - GRBM, T_6 - PGS HV, T_7 - outer radiator, T_8 - SpAmp, T_9 - PGS digital electronics.

in space. The radiators viewed a planar cold screen containing liquid nitrogen that was pumped to produce a temperature near 50 K. This temperature, which was higher than the 3 K of space, was adequate to test the cooler because radiative heat transfer is proportional to T^4 and therefore the heat radiated by the hotter flight cooler was much larger than the heat radiated by the screen. The end of the chamber with the cooler had a liquid nitrogen liner screen to thermally isolate the test units from the walls of the chamber, which were at room temperature. The digital electronics were in the warm end of the chamber. Fig. 3 shows that the inner radiator (curve 1) reached a temperature of about 106 K after 125 hours. The detectors also reached about 106 K as measured by thermistors internal to the detectors. The variations in curves 2,5,6, and 8 starting around 113 hours were caused by changing the aluminum plate temperature to measure the gain dependence of the amplifier.

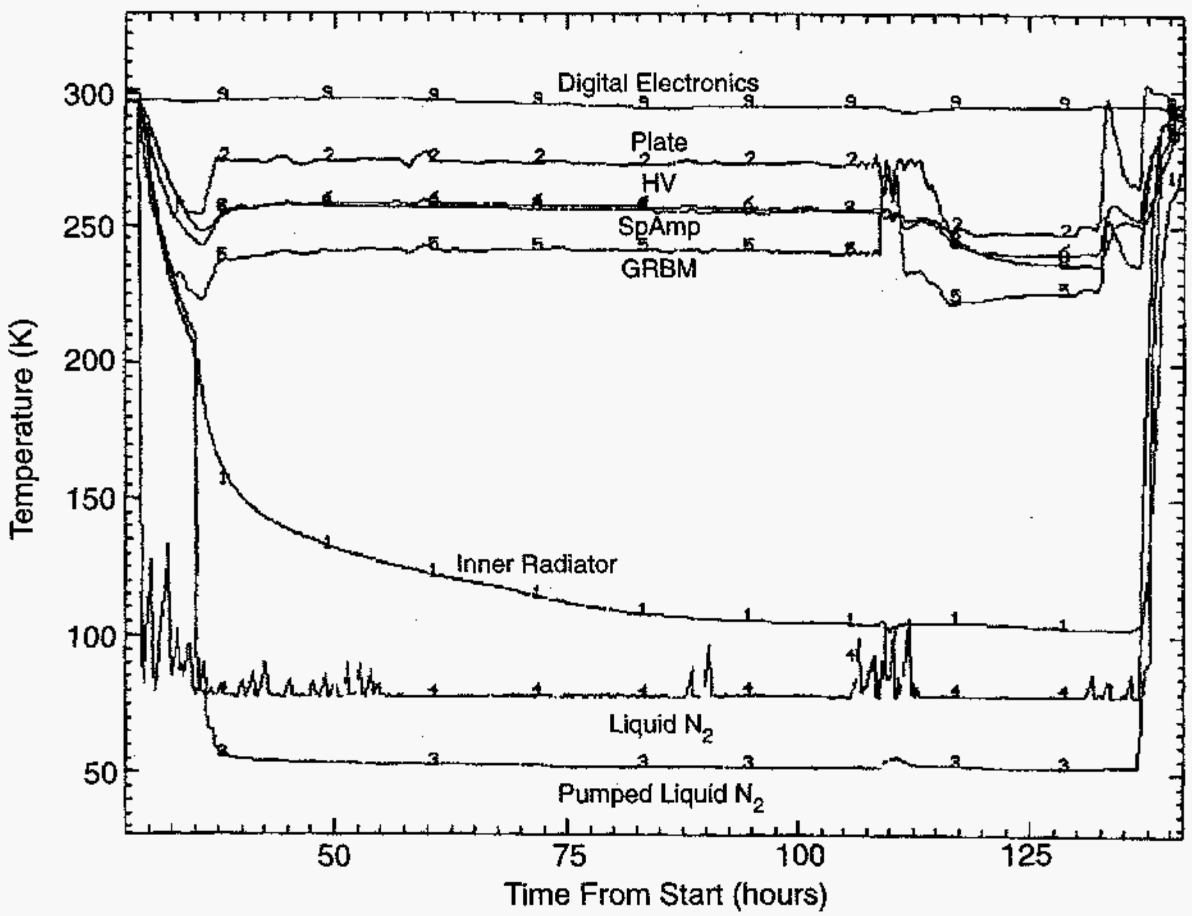


Fig. 3. Final thermal vacuum test. The flight cooler and flight detectors were used.

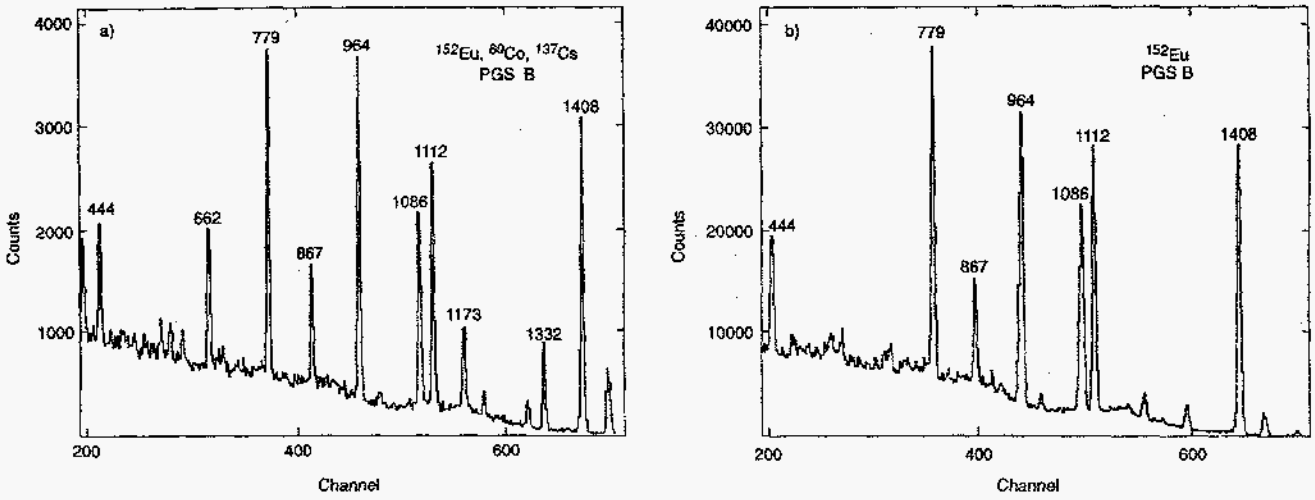


Fig. 4. a) Spectrum of ^{152}Eu, ^{60}Co, and ^{137}Cs measured in a laboratory setup with PGS side B. b) Spectrum of ^{152}Eu measured in the thermal vacuum chamber also with side B.

The operation of the detectors was verified by measuring spectra of a ^{152}Eu source placed between the two crystals.

Fig. 4 b) shows a spectrum measured with side B in the chamber and, for comparison, a) shows a spectrum measured with side B in a laboratory setup. The resolution is 3-4 channels in the chamber and a little better in the laboratory. Similar spectra were obtained for side A. The chamber is particularly electrically noise because of the mechanical pumps, the vacuum electrical feedthrus, the long cables, and the poor grounding configuration. The resolution might improve in space as it did for the Ge detector on Mars Observer.

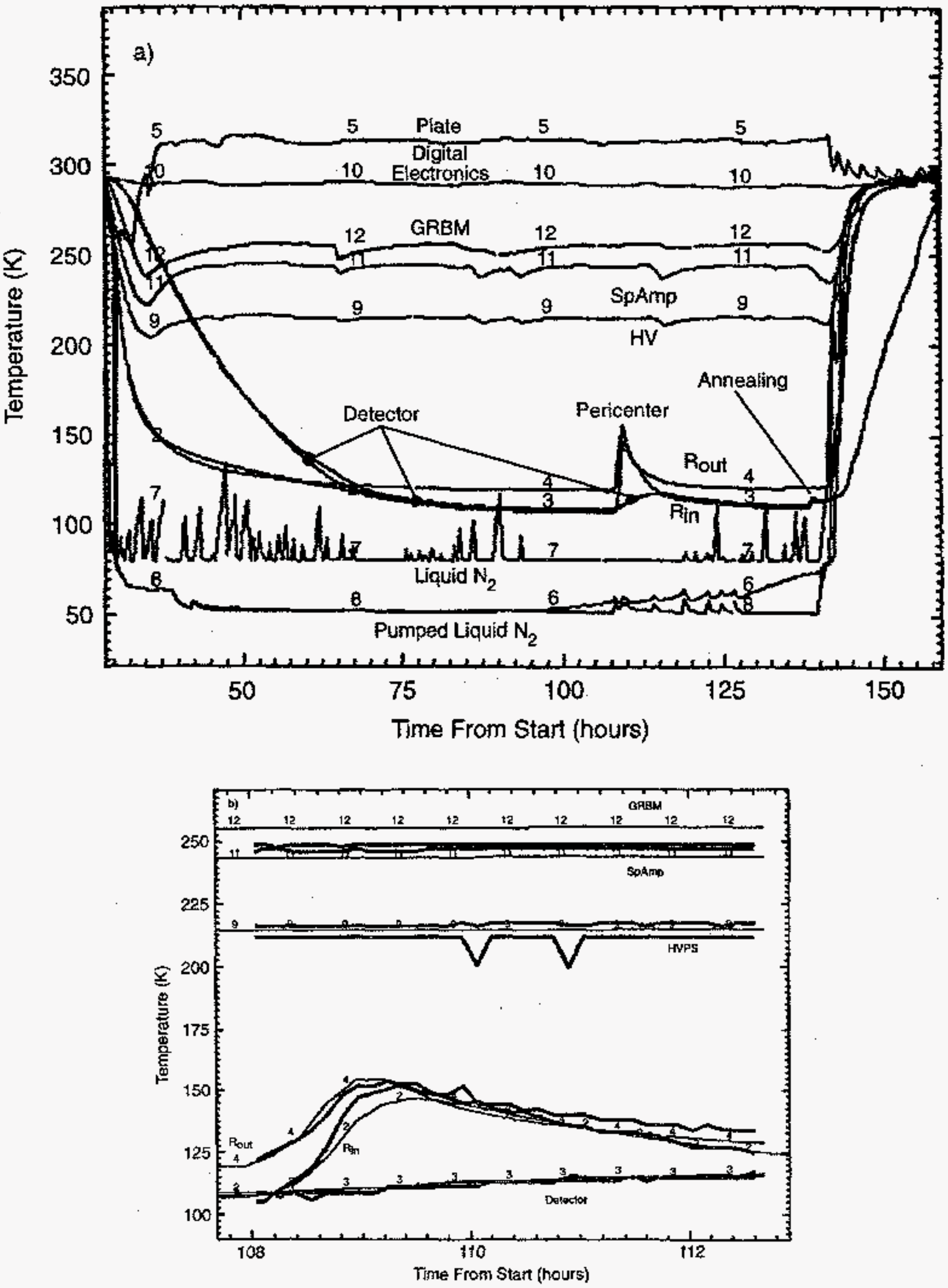


Fig. 5. Thermal vacuum chamber test in November 1995 showing the effect of pericenter heating. In b) the thin lines are for chamber sensors and the thick lines are for PGS sensors; R_{out} is the outer radiator and R_{in} is the inner radiator. The test used the spare flight cooler and the flight detectors.

Another thermal vacuum chamber test was performed in November 1995, which yielded information about the pericenter heating as well as other data. The test used the flight detectors, temporarily integrated with the spare flight cooler. The setup was similar to the one shown in Fig. 3, but the temperature monitors are labeled differently. Electrical heaters were attached to the inner and outer radiator to simulate the pericenter heating. Fig. 5 shows that the detectors reached a temperature of 108 K, a little higher than in the test in June 1996 probably because of the added heat load of the wires for the electrical heaters. During the pericenter simulation the highest temperature of the detectors was 118 K. At about 138 hours the annealing heaters power was briefly turned on to verify their performance, resulting in a small increase in the temperatures of the detectors. Spectra of a ^{56}Co source verified the operation of the detectors.

5. CALIBRATIONS

The germanium detectors require two types of calibrations because they will be used to measure line spectra and continua. Line spectra are expected from Mars and solar flares. Gamma-ray burst spectra might not have any photopeaks but only continua, which require response functions for analysis. By definition, response functions contain both absolute efficiency and the line shape for a monoenergetic gamma ray. For PGS, both the electronics and the response to radioactive sources must be calibrated.

It is necessary to calibrate the ADC (Analog to Digital Converter) and its associated electronics because the ADC uses successive approximation, which results in slightly varying channel widths and channel positions. A high precision pulse generator, which could supply about 16 voltage levels per channel, was used to measure the channel widths and positions. The widths varied a maximum of 20% but the uncertainty in measuring their widths was 2 to 3%. This calibration is built into the software for processing the data.

The gamma-ray sources used for calibration include ^{241}Am, ^{137}Cs, ^{57}Co, ^{60}Co, ^{54}Mn, ^{22}Na, and ^{88}Y, which have simple spectra for measuring the detector response. We also used two multi-line sources: ^{56}Co covers the range 847 to 3254 keV and a mixed source of ^{125}Sb, ^{155}Eu, ^{54}Mn, and ^{60}Co covers the range 36 to 1332 keV. We plan to extend the calibration to high energy using the reaction $^{13}C(\alpha,n)^{16}O$ to give a point at 6129 keV and the reaction $^{56}Fe(n,\gamma)$ to produce gamma-ray lines at 7631 and 7645 keV as well as 1612 and 1725 keV. The lower energy lines are used to normalize the high energy points to the lower energy photopeak efficiencies.

These measurements with the detectors in laboratory cryostats for cooling used a low-mass fixture attached to each cryostat to hold each source 25 cm from the front surface of each crystal. Each source was positioned at the angles 0° (on axis), 30°, 60°, 90°, 120°, and 150°. Because the flange on each germanium detector is approximately square, two azimuthal angles were used: one through a corner of the square and the other midway between the corners. Data were acquired with laboratory electronics connected to an EG&G Ortec ACE 8192-channel analyzer board in a 486 PC running the Maestro II software.

We have limited the total number of measurements because the two flight detectors and the spare have very similar geometries and thus are expected to have similar efficiencies and responses. Using the low-energy sources listed above we made 3 measurements on flight detector SN 2596, 38 on flight detector SN 2600, and 28 on spare detector SN 2570. The flight detectors, which are integrated with the flight cooler, are not available for additional calibration. The spare detector is still in Moscow for testing of the flight electronics after integration with the spacecraft, for additional EMC (electromagnetic compatibility) testing, and to be readily available until launch. After launch we plan to return the spare to the US, where the sources are located, to complete the calibration.

The response functions and photopeak efficiencies determined in these experimental measurements can not be used without additional corrections for attenuation and scattering by the cryostat. The geometry of the detector and cryostat is cylindrically symmetric from 0 to 90° but more complicated at larger angles because the detector flange is square, the detector is supported by four copper bars, and the electronics mounted on the detector can are very asymmetric. We plan to use Monte Carlo calculations supplemented by analytic approximations above about 0.5 MeV to make these corrections. For space data, additional corrections might be necessary for the cooler and other spacecraft structures near the detectors.

We have also taken some calibration data when the two flight detectors were not in their cryostats. The detectors were integrated with the flight cooler and cooled in the thermal vacuum chamber as described in Section 4. above. A ^{152}Eu source was placed between the detectors, which are separated by 40 cm, and supported by the inner radiator. Figure 4 b) shows several of the gamma-ray lines that will be compared with the predictions of the Monte Carlo calculations to verify the modeling of the detectors. For an additional comparison (Fig. 4 a)), a measurement was also made with the two flight detectors in their cryostats, separated by 40 cm, with the same ^{152}Eu source. The measurement in the chamber and without the cryostats does not exactly reproduce the geometry in space because the gamma rays are not arriving in a parallel beam and the spacecraft geometry is not included, but it is the most realistic measurement we have.

6. FLIGHT OPERATIONS

Several days after launch from the Baikonur cosmodrome, the PGS detectors and cooler will be deployed from the solar panel. After ~5 days when the detectors have cooled to below about 120 K, the high voltages on the crystals will be slowly increased and the performance monitored during several interactive sessions from the Yevpatoriya tracking station. The operational voltages will be as low as possible, probably about -2500 V, while still high enough to ensure full depletion and good energy resolution.

The PGS instrument allows data to be acquired in several different modes. In the pericenter mode, when the spacecraft is within ~1000 km of the surface, energy spectra are acquired in selectable intervals from 2-17 minutes. In the background mode, which is to be used during the cruise phase of the mission and during a major faction (about 42 of the 43 hours) of the orbital period, the same data are acquired in intervals from 8-134 minutes. In burst mode, which will usually be triggered by a rapidly-rising counting rate, the pulse height and time with a resolution of 1/262144 s is stored for each photon over an interval of 32 or 64 s. There is also a pre-trigger memory that contains data for <3800 previous photons, which is read out when a trigger occurs. More details of these modes are presented elsewhere.[14]

The performance of the PGS instrument can be determined from background spectra. Gamma-ray lines are expected from cosmic rays reacting in (e.g., 1.63-day ^{69}Ge) and around (e.g., 2.6-year ^{22}Na) the crystals, impurities such as Th, U, and ^{40}K, and prompt reactions, such as ^{48}Ti(n,nγ)^{48}Ti.

7. SUMMARY

The PGS instrument should provide significant advances in our understanding of three space science topics: Mars, gamma-ray bursts, and solar flares. PGS will provide the first global high-energy-resolution spectra of gamma-ray lines from the Martian surface. The planetary results will be less than that expected by the Mars Observer GRS because of the elliptical orbit and the lack of a charged-particle anti-coincidence "shield" around the Ge detectors. However the abundances of a number of elements, such as H, O, Mg, Si, S, Cl, K, Ca, Fe, Th, and U, should be determinable for several large regions of Mars that can answer some basic questions about this very interesting planet.

The operation of a high-energy-resolution instrument for a long period of time should enable several spectra to be obtained of cosmic gamma-ray bursts and solar flares. The fine-scale features in gamma-ray burst spectra might be diagnostic for these poorly understood high-energy astrophysical phenomena. The measurements of nuclear lines in solar flares might help in understanding the mechanism of solar flares. The relative arrival times of gamma rays observed by PGS and TGRS on the WIND spacecraft[17] should provide better constraints on the location of gamma-ray bursts and solar flares.

As described in this report, the PGS instrument has been improved and extensively tested during the delay of the launch originally scheduled for 1994. PGS is ready for launch in November 1996.

8. ACKNOWLEDGMENTS

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9. REFERENCES

1. V. I. Moroz *et al.*, "Missions to Mars in 1996-98," *Adv. Space Res.*, in press.

2. W. V. Boynton *et al.*, "Science applications of the Mars Observer gamma-ray spectrometer," *J. Geophys. Res.*, Vol. 97, pp. 7681-7698, 1992.

3. R. C. Reedy *et al.*, "Expected γ ray emission spectra from the lunar surface as a function of chemical composition," *J. Geophys. Res.*, Vol. 78, pp. 5847-5866, 1973.

4. R. C. Reedy, "Planetary gamma-ray spectroscopy," *Proceedings, 9th Lunar and Planetary Science Conference*, pp. 2961-2984, Pergamon Press, New York, 1978.

5. J. Masarik and R. C. Reedy, "Gamma ray production and transport in Mars," *J. Geophys. Res.*, Vol. 101, in press, 1996.

6. L. G. Evans and S. W. Squyres, "Investigation of Martian H_2O and CO_2 via orbital gamma ray spectroscopy," *J. Geophys. Res.*, Vol. 92, pp. 9153-9167, 1987.

7. S. W. Squyres and L. G. Evans, "Effects of material mixing on planetary gamma ray spectroscopy," *J. Geophys. Res.*, Vol. 97, pp. 14701-14715, 1992.

8. A. E. Metzger, "Composition of the Moon as determined from orbit by gamma-ray spectroscopy," *Remote Geochemical Analysis: Elemental and Mineralogical Composition*, ed. C. P. Pieters and P. A. J. Englert, pp. 341-365, Cambridge Univ. Press, New York, 1993.

9. Yu. A. Surkov *et al.*, "Analysis of the gamma radiation of Martian rocks based on the data of the Mars 5 spacecraft," *Cosmic Research*, Vol. 18, pp. 453-460, 1981.

10. C. d'Uston *et al.*, "Observations of the gamma-ray emission from the Martian surface by the APEX experiment," *Nature*, Vol. 341, pp. 598-600, 1989.

11. Yu. A. Surkov *et al.*, "Determination of the elemental composition of Martian rocks from Phobos 2," *Nature*, Vol. 341, pp. 595-598, 1989.

12. J. I. Trombka *et al.*, "Analysis of Phobos Mission gamma-ray spectra from Mars." *Proceedings, 22nd Lunar and Planetary Science Conference,*" pp. 23-29, Lunar and Planetary Institute, Houston, 1992.

13. I. G. Mitrofanov *et al.*, "A high precision gamma-ray spectrometer for the MARS-94 mission," *Acta Astronautica*, Vol. 35, Suppl., pp. 119-126, 1995.

14. I. G. Mitrofanov *et al.*, "High precision gamma-ray spectrometer PGS for Russian interplanetary mission to Mars," *Adv. Space Res.*, Vol. 17, No. 12, pp. (12)51-(12)59, 1996.

15. I. G. Mitrofanov *et al.*, "The MARS-96 PGS germanium gamma-ray spectrometer," *Lunar and Planetary Science XXVII*, pp. 885-886, Lunar and Planetary Institute, Houston, 1996.

16. J. J. M. in't Zand *et al.*, "The MOXE x-ray all-sky monitor for Spectrum-X-Gamma," *SPIE*, Vol. 2279, pp. 458-468, 1994.

17. A. Owens *et al.*, "High-resolution Ge spectrometer for gamma-ray burst astronomy," *Space Science Reviews*, Vol. 71, No. 1-4, pp. 273-296, 1995.

18. M. Koenen *et al.*, "Radiation damage in large-volume n- and p-type high-purity germanium detectors irradiated by 1.5 GeV protons," *IEEE Trans. Nucl. Sci.*, Vol. 42, pp. 653-658, 1995.