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Document Number VOY - C1 - TR4A
1 June 1967

**SUPPLEMENT TO SCIENCE INSTRUMENT
RADIATION SENSITIVITY REPORT NUMBER I**

RTG STUDY - VOYAGER TASK C

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4800 OAK GROVE DRIVE
PASADENA, CALIFORNIA

UNDER JPL CONTRACT NO. 951112
MODIFICATION NO. 3

GENERAL ELECTRIC

MISSILE AND SPACE DIVISION
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INTRODUCTION

This document serves as a supplement to the Science Instrument Radiation Sensitivity Report No. 1 (VOY-C1-TR4). Presented herein are estimates of shielding and deployment distance for RTG radiation attenuation to permit acceptable operation of certain radiation detecting instruments. Information supplied by JPL on the characteristics of a gamma-ray spectrometer served as the basis for this study.

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SUPPLEMENT

1.0 INSTRUMENT CHARACTERISTICS

The information furnished by JPL in response to a GE request regarding the gamma-ray spectrometer is as follows:

CHARACTERISTICS OF A GAMMA-RAY SPECTROMETER FOR SPACE EXPERIMENTS

1) Operational Description

Purpose: (a) detection of gamma radiation with energies from 50 Kev to 10 Mev.

(b) analysis of the energy spectrum of the detected radiation by means of an electronic pulse-height analyzer.

Application: (a) determination of the composition of planetary surfaces by analysis of the gamma radiation emitted by the surface.

(b) investigation of the physical conditions in extra-solar-system objects by analyzing the gamma radiation they emit.

Operating Mode: passive photon counting with electronic sorting of associated electrical pulse-heights. Coincidence shielding will be included to reduce the background. The instrument will be operated in both the coincidence and noncoincidence modes.

Time Resolution Capabilities: two incident photons can be resolved if they impinge upon the crystal at times separated by more than 0.5 microseconds.

Spatial Resolution Characteristics: In the absence of collimation, photons can be detected arriving at the crystal from all directions, i. e., with 4π solid angle. A heavier and more elaborate detector, which could be used if weight permits, would provide 10-20° half angle collimation.

2) Layout and Materials

The scintillation detector must be placed as far as possible from the main mass of the spacecraft to reduce the contribution of cosmic ray-induced activities. Materials in the

immediate vicinity of the detector should be low in natural radioactivity. The sensing crystal of the detector system must have an unobstructed view of the object under investigation.

3) Dynamic Range

- a) Energy - 20 Kev to 100 Mev photons can be detected. Because of low quantum efficiency at high energies, poor energy resolution at the lowest energies, and the lesser importance of the energy extremes for planetary application, the actual operating range for a Voyager experiment would be within these limits (see 1a).
- b) Flux - 10^{-5} photons per $\text{cm}^2 \cdot \text{sec}$ to 10^6 photons per $\text{cm}^2 \cdot \text{sec}$. The higher flux limit is imposed by time resolving characteristics and is not a concern for space applications due to the low fluxes expected from extraterrestrial objects. The lower flux limit is determined by the background observed in the crystal (i.e., primarily by the shield efficiency and the level of background radiation). Many gamma-ray experiments result only in upper limits to the flux from a celestial object and the lowest possible background resolution is of paramount importance.

4) Primary Dynamic Range

For an actual flight which would observe Mars at a distance of 2,000 miles or less from the surface we would expect 1-10 photons per $\text{cm}^2 \cdot \text{sec}$ in the detector between 0.1 and 10 Mev. The tolerable level of unwanted background flux contributed from sources other than cosmic ray induced activity is on the order of 5×10^{-3} photons per $\text{cm}^2 \cdot \text{sec}$. Mev at 1.5 Mev, the energy of the significant K^{40} line. The allowable contribution at other energies will vary roughly as E^{-2} . If such contributions vary with time the tolerable limits will be lower.

5) Physical Description

At the present state of development the sensor is expected to be a 3" x 3" crystal of NaI (Tl) optically coupled to a single photomultiplier tube. Advances in the state-of-the-art plus an increased payload capability would suggest the use of a substantial volume of active shielding around the detector. This would reduce the unwanted gamma-ray background. The simpler configuration utilizes a shell of plastic scintillator, which is viewed by a second photomultiplier tube. Gamma-ray photons are absorbed very weakly in the plastic scintillator while charged particles are detected with high efficiency. The charged particle flux can therefore be distinguished from gamma-rays and eliminated. Energy deposited by gamma-rays in the scintillation crystal is transformed into light. The light becomes an electronic pulse in the photomultiplier where it is multiplied and emerges as an analog signal. The analog output from the photomultiplier tube eventually is converted into digital form by the electronics in such a manner that the digital number is proportional to the energy of the incident gamma-ray.

6) Sensor Efficiency

A function of sensor volume and the incident gamma-ray energy. It will vary from roughly 2-90% over the range of interest. The charge particle efficiency will be close to 1, that of neutrons less than 5%. A source of neutrons presents a problem; neutrons are difficult to discriminate against and will activate the sensor and surrounding materials.

7) Response Time

On the order of 0.1 - 1 microsecond in the sensor and 1-100 microseconds in the electronics.

8) Calibration

Calibration will be performed by a weak source of radioactivity which emits at a known energy and possesses good resolution and a minimum of continuum.

9) Electronics

Conventional amplification and digitization.

10) Parts List

Not available.

2.0 SHIELDING CALCULATIONS

Radiation flux attenuation to levels suitable for instruments of the gamma-ray spectrometer type is discussed below. Only attenuation by passive shielding techniques is considered. Although active techniques might also be applied, e. g. , those employing coincidence circuitry, they are not considered here.

The allowable background flux level over applicable energies can be calculated from

$$K \int_{E_1}^{E_2} E^{-2} dE = -KE^{-1} \Bigg]_{E_1}^{E_2} \quad (1)$$

where E = photon energy
 K = constant

It is assumed that the allowable contributions at all energies vary as E^{-2} . The value of K was established by setting $-KE^{-1}$ (evaluated from $E_1 = 1$ Mev to $E_2 = 2$ Mev) equal to 5×10^{-3} photons.cm⁻².sec⁻¹. The total allowable background flux between 0.1 and 10 Mev may be shown to be 9.9×10^{-2} (approximately 10^{-1}) photons.cm⁻².sec⁻¹. By evaluating Equation (1) between the limits of 0.05 and 10 Mev, the integrated allowable background flux becomes 0.199 (approximately 0.2) photons.cm⁻².sec⁻¹. These integrated background flux level specifications are far too small to permit the use of the simple NaI (Tl) sensor anywhere on an unshielded spacecraft which is powered by RTG units. Reference 5 (Figure 2-3 and Table 2-1) presents evidence that the dose rates over the exterior surface of the Voyager bus with 600 electrical watts available from Pu²³⁸ – fueled RTG units are of the order of hundreds of neutrons.cm⁻².sec⁻¹ and 10^{-2} rad. hr⁻¹ of gamma dose.

Relative to the use of shielding to provide flux attenuation, lead and LiH shield thicknesses were computed at distances of 10, 20, 50 and 100 meters from the spacecraft centerline. The thicknesses were designed to permit integrated fluxes of 0.1, 1.0, and 10 gamma rays and neutrons per cm² per sec¹ to pass through the shield and into the NaI (Tl) crystal. The lead gamma shield thicknesses were computed from the well-known relation

$$I = I_0 e^{-\mu \rho t},$$

where I_0 is the initial intensity of gamma radiation entering a shield and I exits from the other side. μ is the mass absorption coefficient (for narrow beam attenuation and disregarding Rayleigh scattering), values of which were obtained from References 6 and 7. For these studies the value of μ at 1.0 Mev was assumed. ρ is the material density and t the thickness. Dose buildup factors (D), due primarily to Compton scattering, were obtained from Reference 6 for Pb. The buildup factor for LiH in thicknesses greater than about 10 cm was assumed to be 2. For smaller thicknesses, D was assumed to be 1.5.

Neutron attenuation was computed by utilizing the relatively simple fast removal theory. Details of the method, applicable for shields containing hydrogen, are available from many sources including References 6 and 8. This theory assumes that a neutron flux N_0 is attenuated to flux N following passage through a shield of thickness t of a material whose fast removal cross section is Σ . The neutron shield thickness t was computed from

$$N = N_0 e^{-\Sigma t}$$

The value of Σ is dependent on the neutron spectrum and the experimental conditions under which it was measured. Most measurements have utilized the U-235 fission spectrum where the most probable neutron energy is about 1 Mev. The Pu⁻²³⁸ spectrum is harder with a most probable neutron energy of approximately 2.5 Mev. Very few studies of Σ for the Pu⁻²³⁸ spectrum have been made. See, for example, Reference 9. Following a search of the literature, it was decided that a value $\Sigma = 0.10 \text{ cm}^{-1}$ for LiH would be utilized in this study. For Pb, $\Sigma = \overset{0.115}{\cancel{3.5}} \text{ cm}^{-1}$ was selected.

The neutron and gamma spectra which served as source terms were those computed (Reference 5) at a point in the plane of the RTG's, 10 meters from the spacecraft centerline. The source spectra are shown in Table A-1, based upon Pu⁻²³⁸ fuel characteristics. Flux intensities at larger than the 10 meter distance are based on $1/R^2$ attenuation.

Table A-1. Gamma Ray and Neutron Flux Source Terms

<u>Gamma Ray Fluxes</u>	
Energy Group Limits (Mev)	Photons.cm ⁻² .sec ⁻¹
4.0 - 7.0	4.09
2.7 - 4.0	5.16
1.9 - 2.7	8.67
1.3 - 1.9	10.17
0.9 - 1.3	12.74
0.8 - 0.9	114.79
0.5 - 0.8	304.68
0.2 - 0.5	1.62
0.13 - 0.18	11.10
0.7 - 0.10	0.0
Total: 0.04 - 7.0	4.73x10 ²
<u>Neutron Fluxes</u>	
Energy Group Limits (Mev)	Neutrons.cm ⁻² .sec ⁻¹
8.0 - 13.0	0.1
5.0 - 8.0	2.3
3.0 - 5.0	13.5
1.0 - 3.0	27.9
0.0 - 1.0	15.7
Total: 0.0 - 13.0	59.5

Figure A-1. Shield Thickness Versus Boom Length

These results are preliminary, and serve only to scope the magnitude of the problem. Hand calculations obviously do not solve the Boltzmann equation for gamma and neutron transport with as much accuracy as is available through numerous computer programs. The total thicknesses which were computed by the techniques described above are plotted in Figure A-1. Table A-2 identifies the thickness of each material required to attenuate the incident radiation beam, consisting of photons and neutrons, to the indicated level.

Table A-2. Shield Thicknesses

Distance: (centerline to Boom Tip)	Attenuation								
	$0.1 \text{ cm}^{-2}.\text{sec}^{-1}$			$1.0 \text{ cm}^{-2}.\text{sec}^{-1}$			$10 \text{ cm}^{-2}.\text{sec}^{-1}$		
	Pb	LiH	Total	Pb	LiH	Total	Pb	LiH	Total
10 Meters	12.4 cm	63.8 cm	76.2 cm	9.2 cm	40.8 cm	50.0 cm	6.1 cm	18.5 cm	24.6 cm
20 Meters	10.6 cm	50.0 cm	60.6 cm	7.3 cm	27.0 cm	34.3 cm	4.0 cm	10.5 cm	14.5 cm
50 Meters	7.9 cm	31.7 cm	39.6 cm	4.9 cm	10.5 cm	15.4 cm	1.4 cm	-	1.4 cm
100 Meters	6.0 cm	17.8 cm	23.8 cm	2.5 cm	6.0 cm	8.5 cm	-	-	-

At the distance of 73 meters geometrical attenuation reduces the flux level to $10 \text{ photons.cm}^{-2}.\text{sec}^{-1}$. Between 20 and 50 meters it becomes no longer necessary to utilize LiH shielding. This explains the change in slope of the lower curve of Figure A-1.

3.0 SHIELD WEIGHT

Shielding is interjected between the radiation source and sensor in such a manner as to obscure the apparent image of the source as viewed from the sensor. This is commonly referred to as shadow shielding. In conjunction with the shield thicknesses estimated in Figure A-1, shield weight is determined by the solid angle shape closest to the sensor that provides this total shadowing. Figure A-2 illustrates two cases of this first approximation for determining shield weight. The sensor is located by appropriate deployment devices at some distance L from the main spacecraft axis in a plane coincident with that formed by the RTG's. This plane is believed to be the best for sensor location because of the shadowing of certain RTG's by other RTG's and the fact that the source image, basically in the form of a diametral band, is smallest as viewed from remote locations. Assuming the use of a scintillator in the form of a 3-inch cube, two types of shields are considered for purposes of bounding estimated shield weights:

Case 1: The solid angle shield shape is only sufficient to attenuate the primary gamma and neutron radiation from the RTG's. The shield takes the form of a pie segment.

Case 2: The solid angle shield shape attenuates both the primary RTG radiation and secondary radiation resulting from interaction with the spacecraft materials. As a worst case the secondary radiation is assumed to be similar to the primary radiation and therefore similar thicknesses are used throughout the shield. The shield takes the approximate form of a cone frustum.

Figure A-2. Instrument Shadow Shielding

The shield weight as a function of distance L is shown on Figure A-3 for the two cases. As indicated earlier these results are only intended to bound the problem. An optimized design would require extensive calculations, probably with computer techniques, to resolve the secondary radiation effects and the extent of shielding required. More optimum weights might result with divided shield techniques in which a portion of the shield is located near the source as well as near the sensor.

For the cases described above, the shield is assumed to be composed of alternating layers of lead and lithium hydride. Lead is a good gamma ray shield, while LiH is one of the more efficient solid neutron shields. Other materials may be chosen. The material selection must

Figure A-3. Shield Weight Versus Boom Length

be optimized so that no sections are particularly strong secondary radiation emitters. Although hydrogen is the best neutron shield, it emits the rather intensive 2.2 Mev gamma ray by radiative capture. By using LiH, a higher fraction of the low energy neutrons are captured by lithium, with a relatively large absorption cross section. Isotopic Li^6 has a very high absorption cross section for low energy neutrons and a very small probability of secondary gamma emission. Li^7 , found along with Li^6 in natural Li, emits bremsstrahlung. An

optimized neutron shield may utilize Li^6H . Lead produces several high energy gamma rays, including but not restricted to the following energies: 0.569, 0.900, 1.63, 2.34, 2.75, 3.6, 2.62, 3.2, 3.47, 3.79, 4.0, 6.73, and 7.38 Mev. Fortunately, however, the cross sections for the production of each of these energies ranges from very small to small, and the number density of neutrons from RTG's which are capable of producing most of these gamma rays is relatively small. So gamma production in lead, although a problem, is not a major problem.

Materials selection for shields and radiation sensitive instrument sensors must be optimized with reference to other photon and charged particle producing mechanisms. These factors are briefly referred to in Section 2, Reference 1. Manufacturing, safety, and other considerations must also be analyzed. LiH is, for example, a highly reactive chemical which must be encased within a metal envelop to keep away O_2 , H_2O , and prevent outgassing.

4.0 INSTRUMENT AND SHIELD DEPLOYMENT

Flux attenuation is improved by increasing the distance between the radiation source and sensors. Methods for achieving this distance deployment of the sensor and/or shielding are described below along with estimates of the deployment mechanism weight.

Various types of deployment devices can be considered for this application. They include:

- Telescoping cylinders
- Pantographs
- Folding beams
- Self extruding plastic
- Inflatable structures
- Overlap tubes (S. T. E. M. 's)
- Interlocking overlap tubes
- Closed wall tubes, flattened and rolled

The S. T. E. M. type overlap tubes and interlocking overlap tubes were selected for further study below for the following reasons:

- a. They provide the lightest possible boom system for the lengths required for this system (20 to 500 feet) and for the relatively moderate loading conditions imposed.
- b. The space requirements within the spacecraft would be smaller than other type systems for the lengths under study.
- c. They are flight proven systems (Ref: A. T. S. , G. G. T. S. , N. R. L. Gravity experiment and others).
- d. They are the only types of systems selected by NASA for extreme lengths (R. A. E. , 800 feet).
- e. Deployment rates and acceleration may be controlled.
- f. The booms can be retracted and/or their length can be adjusted to any position required up to fully extended length (and cycled many times if necessary).

The following design conditions were used for this study:

- a. Maximum spacecraft angular acceleration after boom deployment = 2.25×10^{-4} rad/sec (Task B)
- b. Maximum spacecraft angular velocity during deployment = 0.18 deg/sec (Task B)
- c. Maximum spacecraft inertia just prior to boom extension = 4044 slug-ft²
- d. Maximum tolerable boom tip deflection (angular) under load = $\pm 10^0$
- e. Required tip masses (shielding) may be as high as 500 pounds

The following constraints were used in selecting boom configurations for the various loading conditions:

- a. The maximum cantilever end slope under spacecraft acceleration loads shall not exceed 10^0 .
- b. The maximum applied bending moment shall not exceed 1/3 of the critical ultimate bending moment for the boom selected.
- c. Applied bending moments arise from spacecraft accelerations after deployment, coreolis forces during deployment, and gravity gradient torques.

It was found in all cases that the governing criterion was the bending stiffness dictated by constraint (a).

The S. T. E. M. type overlap boom is one which is formed by a flat strip of thin material which assumes a tubular shape of high strength when extended. For storage the flattened strip is coiled on a drum. Thus, a boom of several hundred feet can be stored on a drum only a few inches in diameter and the drum width will be approximately 4 times the boom diameter. The only added component space required is for a drive motor and a set of guides forward of the storage drum. This guidance length is usually 10 to 12 times the boom diameter. For booms longer than 20 feet this ratio of boom length to stowed package size can be matched by no other type of extendible boom.

When erecting the stowed boom, the drive motor turns the drum and allows the prestressed strip to form its natural tubular shape as it moves through the guides and extends itself from the spacecraft.

For booms where torsional stiffness or position is important a slight modification is introduced wherein one edge of the strip is notched and engaged in slits in the other edge. This has the effect of causing the boom to behave like a closed wall tube in torsion.

Figure A-4. Boom and Deployer Weight (Exclusive of Shield Weight)

Figure A-4 attached presents a plot of required boom system weight vs. boom length for various boom tip weights. This set of curves was generated based on:

- Boom bending stiffness required to limit end slope to 10^0 for the various weights and lengths under the applied loads,
- Boom strength required to limit applied loads (acceleration and coreolis) to $1/3$ of boom critical bending moment,
- Boom deployer weights required for the various sizes and lengths of booms selected,
- Tolerable boom diameter to wall thickness ratios.

The sizes of booms required varied from 0.5 inch diameter and 0.003 inch wall thickness to 3.0 inch diameter and 0.010 wall thickness. In all cases, the material selected was stainless steel for stiffness reasons. Where absolute magnetic purity is required, beryllium copper can be used with slight increases in weight.

The added weights of the boom mechanisms and shielding as a function of distance from the main spacecraft axis are shown in Figure A-5 with parameters of attenuated flux level and the two shielding approaches discussed earlier. A cross plot of minimum weight systems is shown on Figure A-6.

Figure A-5. Total Weight Versus Boom Length

Figure A-6. Minimum System Weight and Boom Length for a Given Flux

5.0 CONCLUSIONS

The results presented herein provide preliminary estimates of weight and distance requirements needed to accommodate radiation detecting instruments in an RTG powered Voyager spacecraft. These results should not be interpreted as establishing the feasibility of the approach. Many other factors would require examination including the effects of gravity gradient torques, thermal bending of long booms, signal and power transfer to the deployed instrument, and when in the mission profile it is practical to deploy the instrument. Regarding this last item, the weight estimates are based on boom systems that could not withstand orbit insertion or orbit trim thrust loads. Thus, unless there was high assurance that the instrument could be retracted reliably, the instrument could not be deployed until after the final orbit trim maneuver.

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