THE PROGRAM AT JPL TO INVESTIGATE THE NUCLEAR INTERACTION OF RTGs WITH SCIENTIFIC INSTRUMENTS ON DEEP SPACE PROBES*

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A major concern in the integration of a radioisotope thermoelectric generator (RTG) with a spacecraft designed to explore the outer planets is the effect of the emitted radiation on the normal operation of scientific instruments. This paper discusses the program presently being conducted at the Jet Propulsion Laboratory to evaluate these effects. The problem is being approached in both an analytical and experimental manner. The necessary techniques and tools have been developed to allow accurate calculation of the neutron and gamma spectrum emanating from the RTG. The specific sources of radiation have been identified and quantified. Monte Carlo techniques are then employed to perform the nuclear transport calculations. The results of these studies are presented.

An extensive experimental program has been initiated to measure the response of a number of scientific components to the nuclear radiation. Such devices as Geiger Muller tubes, solid state detectors and electron multipliers have been identified as being most probable for use on these missions and extremely sensitive to gamma radiation. Experiments on these devices are being conducted in the JPL radiation laboratory. The capabilities of this laboratory are discussed as well as the results of some of the experiments.

The technique used to measure the response of instruments is to irradiate them with monoenergetic radiation sources. The energy range of interest is between 275 kev to 2800 kev. Appoximately seven isotopes have been selected which provide emissions in this range. Analytical techniques have been developed which fold the measured energy response of the instrument with the calculated energy spectrum emitted by the RTG. Shielding studies are then performed to determine the thickness of shield required to reduce the spurious count level of the instrument to an acceptable level.

The final design must be qualified by irradiating the instrument with the polyenergetic spectrum emitted by the Pu-238 fuel capsule. Since actual fuel capsules are not generally available and since the spectrum from a generator will change with time due to aging of the fuel (spectrum actually becomes harder and more intense due to buildup of the daughter products of the impurity Pu-236) it becomes more practical to use simulated sources.

With the use of isotope powered generators it is now possible for NASA to conduct exploration of planets too remote from the sun to effectively use solar array power concepts. One such set of missions under consideration by the Jet Propulsion Laboratory is the outer planet grand tour missions having possible launches in the 1976 - 1979 time period. The inclusion of isotope systems on these spacecraft introduces a heretofore unconfronted problem to the Laboratory. The radioisotope used as the heat source emits both neutron and gamma radiation as a result of its natural decay. This radiation will have a significant effect on the operation of science instruments designed to measure low level particulate and short wave-length electromagnetic radiation within the interplanetary environment.

In preparation to confront this new environment, the Laboratory has directed a portion of its R&D activities to help define the exact nature of the problem and to develop technical tools and facilities to carefully study and resolve any potential interference which may exist. Over the past three years a rather extensive radiation program has evolved. The purpose of this paper is to give a brief review of the work that has been performed and to indicate the areas of study that are presently underway in the investigation

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of the RTG-science interference.

SOURCES OF RADIATION

The gamma and neutron field in the vicinity of an RTG originates primarily from the radioactivity of the Pu^{238} and associated radioactive nuclides in the heat source. Gamma rays emitted by the plutonium dioxide fuel are derived from three prominent sources: (1) Gamma radiation from plutonium isotopes and their decay products exclusive of Pu^{236}. This includes photons produced by the plutonium isotopes due to natural radioactivity, prompt gammas from fission, and the decay of fission products. (2) Gamma radiation from the radioactive decay of Pu^{236} and its daughter nucleus; and (3) Gamma radiation from alpha particle interaction with the O^{18} isotope. The interaction O^{18} (α,n) Ne^{21} produces Ne^{21} in excited states with the subsequent emission of gamma rays.

The magnitudes of these sources were compiled at JPL several years ago by Gingo and Dore (Ref. 1) based on data available in the literature at the time on the decay and emission characteristics of the various isotopes in the fuel. More recently Dore (Ref. 2) updated this information based on recent Pu^{238} experiments conducted at JPL by Reier (Ref. 3). The emission characteristics presently being used by JPL are shown in Table 1.

Table 1 Emission Characteristics of a Plutonium Heat Source

ISOTOPE: 238Pu	
Energy (keV)	γ/dis/sec (x 10^8)
1085.4	0.11
1041.8	0.20
1001.03	1.08
946.0	0.13
941.9	0.58
926.72	0.71
904.37	0.072
883.23	1.270
880.5	0.23
851.7	1.64
808.25 / 805.8	0.999
786.30	4.98
766.39	26.7
742.77	6.35
708.42	0.38
706.1	0.14
299.2	0.07
258.3	0.011
235.9	0.01
207.6 / 200.9	5.0
152.71	$1.27 \cdot 10^3$
99.84	$9.20 \cdot 10^3$
43.50	$3.80 \cdot 10^4$
17.0	$1.30 \cdot 10^7$

ISOTOPE: 239Pu	
Energy (keV)	γ/dis/sec (x 10^7)
770.0	2.0
650.0	8.0
414.0	110.0
375.0	125.0
340.0	66.0
207.0	44.0
125.0	150.0
51.6	700.0
38.6	200.0
17.0	9900.0

ISOTOPE: 212Pb	
Energy (keV)	γ/dis/sec
415.2	0.0016
300.3	0.041
238.4	0.50
176.7	0.0007
116.0	0.0054
ISOTOPE: 208Tl (36%)	
2615.0	1.00
1093.0	0.0046
861.4	0.124
763.0	0.034
584.5	0.876
510.8	0.253
486.0	0.001
277.0	0.091
ISOTOPE: 236Pu	
645.0	$2.40 \cdot 10^{-6}$
570.0	$1.00 \cdot 10^{-6}$
520.0	$1.70 \cdot 10^{-6}$
165.0	$6.60 \cdot 10^{-6}$
110.0	$1.20 \cdot 10^{-4}$
46.0	$4.70 \cdot 10^{-4}$

ISOTOPE: 212Bi		
	β (64%)	α (36%)
Energy (keV)	γ/dis/sec	
1800.0	0.0017	
1621.0	0.0247	
1512.8	0.0061	
1078.2	0.0073	
1073.0	0.001	
952.1	0.0025	
893.9	0.0058	
785.0	0.016	
729.9	0.104	
493.0 / 473.0 / 460.0 / 453.0 / 434.0	0.008	0.0042
328.0		0.00110
288.2		0.0028
288.0	0.005	
40.0	0.02	

Table 1 (Cont'd)

Spontaneous Fission and Fission Product Gammas

Group	Energy Interval (MeV)	Spontaneous	Equilibrium Fission Product γ/sec/gm-PuO_2	Total
1	6.0 - 7.0	$7.120 \cdot 10^0$	0.0	$7.120 \cdot 10^0$
2	5.0 - 6.0	$2.103 \cdot 10^1$	0.0	$2.103 \cdot 10^1$
3	4.0 - 5.0	$6.210 \cdot 10^1$	0.0	$6.210 \cdot 10^1$
4	3.0 - 4.0	$1.834 \cdot 10^2$	0.0	$1.834 \cdot 10^2$
5	2.0 - 3.0	$5.416 \cdot 10^2$	$3.446 \cdot 10^1$	$5.761 \cdot 10^2$
6	1.8 - 2.0	$1.981 \cdot 10^2$	$1.206 \cdot 10^1$	$2.102 \cdot 10^2$
7	1.6 - 1.8	$2.460 \cdot 10^2$	$2.542 \cdot 10^1$	$2.714 \cdot 10^2$
8	1.4 - 1.6	$3.056 \cdot 10^2$	$3.188 \cdot 10^1$	$3.375 \cdot 10^2$
9	1.2 - 1.4	$3.794 \cdot 10^2$	$1.594 \cdot 10^1$	$3.953 \cdot 10^2$
10	1.0 - 1.2	$4.708 \cdot 10^2$	$6.893 \cdot 10^0$	$4.777 \cdot 10^2$
11	0.9 - 1.0	$2.767 \cdot 10^2$	$1.529 \cdot 10^1$	$2.920 \cdot 10^2$
12	0.8 - 0.9	$3.084 \cdot 10^2$	$4.265 \cdot 10^1$	$3.510 \cdot 10^2$
13	0.7 - 0.8	$3.437 \cdot 10^2$	$5.837 \cdot 10^1$	$4.021 \cdot 10^2$
14	0.6 - 0.7	$3.830 \cdot 10^2$	$6.117 \cdot 10^1$	$4.442 \cdot 10^2$
15	0.5 - 0.6	$4.268 \cdot 10^2$	$5.902 \cdot 10^1$	$4.858 \cdot 10^2$
16	0.4 - 0.5	$4.755 \cdot 10^2$	$4.933 \cdot 10^1$	$5.248 \cdot 10^2$
17	0.3 - 0.4	$5.296 \cdot 10^2$	$3.770 \cdot 10^1$	$5.673 \cdot 10^2$
18	0.2 - 0.3	$5.906 \cdot 10^2$	$2.628 \cdot 10^1$	$6.169 \cdot 10^2$
19	0.044 - 0.2	$1.059 \cdot 10^3$	$2.046 \cdot 10^1$	$1.079 \cdot 10^3$
20	0.001 - 0.044	$3.248 \cdot 10^2$	0.0	$3.248 \cdot 10^2$

The neutron field from a Pu-238 heat source is mainly due to (α,n) reactions with low impurity elements associated with the plutonium oxide in the heat source. Of particular concern is the reaction with O^{18}. The smallest neutron contribution is due to the spontaneous fission of the plutonium content and to induced fission reactions. The neutron emission characteristics of a Pu-238 heat source have been studied at JPL and were reported by Taherzadeh in Reference 4. The total neutron yield from spontaneous fission was found to be 2800 n/sec per gram Pu^{238}. The number of neutrons generated from the reaction of alpha particles with impurity elements depends on the type and concentration of these impurities. Table 2 indicates an assumed concentration of impurity elements and their respective yields. The total neutron yield, excluding reactions with the oxygen associated with the PuO_2 compound, is 12,900 n/sec/gm Pu^{238} for the assumed concentration of impurities. Alpha particle reactions with O^{18} in the plutonium compound yields 19,900 n/sec/gm Pu^{238}. Both of these contributions can be decreased by reducing the impurity concentrations (particularly fluorine or by exchanging the O^{18} with O^{16}). The final source of neutrons is as a result of additional fissions induced by the available neutron flux. The yield is highly dependent upon the heat source geometry and can contribute from 15 to 30% of the total neutron field.

There is a continuing effort at JPL to maintain close liaison with the fuel production centers in order to be appraised of the exact impurities existing in the fuel. With this data highly accurate estimates of the neutron and gamma emission characteristics of the heat source can be obtained.

Table 2 Neutron Yields due to (α, n) reactions with Impurities

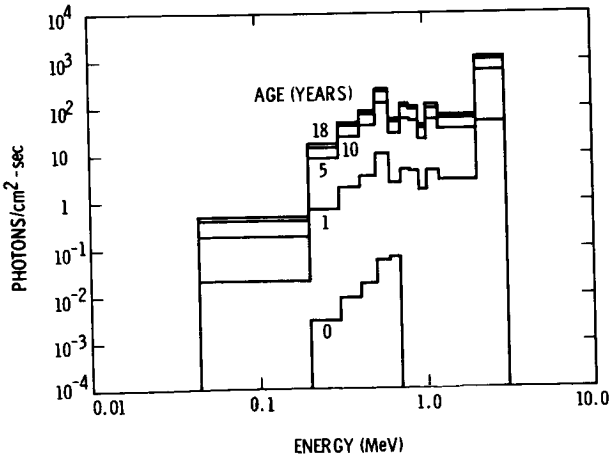
Impurity Elements	PPM in PuO_2	Yield/PPM (n/gm PuO_2/sec/PPM)	Yield
Li	1	4.64	4.64
Be	10	148.80	1488.00
B	20	32.80	656.00
C	500	0.20	100.00
O	11750*	0.10	1175.00
F	250	18.70	4517.50
Na	300	2.00	600.00
Mg	50	1.93	96.50
Al	400	1.08	432.00
Si	441	0.240	105.84
Others	1200	0.03	36.00
		Total	(9211.50 n/sec gm PuO_2 - 12,900 n/sec gm Pu^{238}

*Oxygen concentration due to thO_2 content

DETERMINATION OF RADIATION SPECTRUM FROM RTG

Once the gamma and neutron source strengths are established the field surrounding the RTG is determined by application of Monte Carlo transport codes to a specific geometry. The Monte Carlo code used to perform the calculations at JPL (Ref. 5) utilizes "importance functions" to achieve far better statistics than a straight Monte Carlo simulation would yield for a comparable number of particle histories. The basic technique is to sample heavily those events which are most likely to contribute significantly to the results, while only lightly sampling the others. Generally, one considers the high energy source particles to a disproportionately large extent, since they have the best chance of eventually escaping the RTG.

The neutron and gamma flux spectra from the RTG are determined for 20 energy groups ranging in energy from 1 keV to 7 MeV. The most significant complication in these calculations is the fact that the gamma spectrum will harden with time due to buildup of daughter products in the decay chain of the Pu^{236} which is present in the fuel at a level of about 1.2 ppm. The maximum radiation level occurs about 18 years after fuel processing. Figure 1 shows how the gamma spectrum from a typical fuel capsule will vary as a function of time.



DEVELOPMENT OF SIMULATED RTG

Although JPL has developed computer techniques to accurately calculate the radiation field around an RTG, it is recognized that experiments must be performed with actual sources to substantiate any predictions made regarding the response of instruments to the radiation environment. Since actual Pu-238 fueled sources are not likely to be available on demand at JPL in order to conduct the necessary developmental activities, simulated RTG's are being designed for use. The details of this work are discussed in a paper by Reier (Ref. 6) to be given at this conference. It will suffice here to state that these sources duplicate both the geometry of an actual fuel capsule and RTG as well as the radiation spectrum emitted. This is accomplished with the use of several gamma emitting isotopes, notably Th^{228} as well as Cf^{252} to produce the neutron environment. These sources can then be used to perform full spacecraft-level radiation testing. The advantages of using this type of source are several-fold. First, it allows the radiation testing to be done easily in the developmental process, long before actual fueled generators are available; second, it can be accomplished in a safer manner and with less stringent "nuclear safe" facilities since one is using only millicurie amounts of radioactive material versus the tens of thousands of curies of the Pu 238 alpha emitting isotope; and third and most important, it allows measurements to be made with a source that represents an aged fuel. The gamma radiation spectrum and intensity change with time and reach a maximum after 18 years; it is important to reproduce this worst case situation since the missions considered by JPL for use of RTG's have lifetime approaching 10 years.

SPACECRAFT MAPPING AND TEST

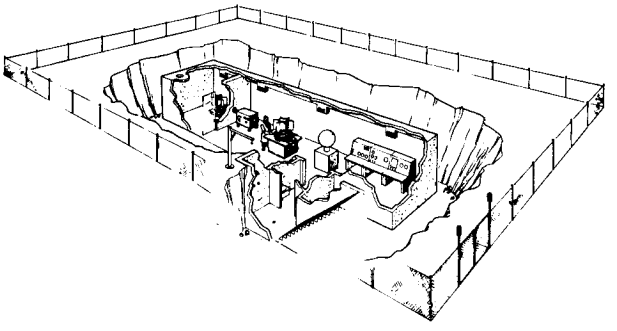
Transport codes similar to those used in determining the radiation field from an RTG are used in mapping a complete spacecraft. JPL has initiated the development of techniques to construct accurate analytical models of the spacecraft. A detailed discussion on this subject will appear at this session of the conference in a subsequent paper (Ref. 7).

As part of its overall program, JPL plans to construct and test an early version of a spacecraft for the purpose of conducting radiation field mapping and instrument shielding studies. This mechanical model spacecraft is known as the Radiation Test Model or RTM and is being developed under the auspices of the Thermoelectric Outer Planet Spacecraft (TOPS) project. With this model, both γ-ray and neutron radiation levels will be obtained throughout a representative TOPS spacecraft configuration. The source of radiation will be the simulated RTGs described earlier in this paper. The objectives of this program are to:

1. Identify in detail the radiation levels at scientific instrument locations.
2. Identify radiation levels at sensitive electronic equipment locations.
3. Investigate the effects of spacecraft configuration changes on shielding and scattering.
4. Provide designers with radiation data for tradeoffs for spacecraft configuration design.
5. Provide experimental verification of existing analytic methods and establish experimental techniques.

RTG RADIATION FACILITY

In order to perform the experimental radiation program at JPL a developmental laboratory has been constructed. This facility allows spectrum measurements to be performed on simulated as well as actual fuel capsules, and enables science components and instruments to be irradiated and their response determined. A sketch of the facility is shown in Figure 2. It is an underground building located in a low population density area at JPL. The overall dimensions of the building are 67' x 16' x 9'. The walls, floor and ceiling are reinforced concrete approximately 14 inches thick. The building is about 5' below ground level.



JET PROPULSION LABORATORY RADIOISOTOPE THERMOELECTRIC GENERATOR (RTG) TEST LABORATORY

This developmental laboratory is equippea with all of the necessary radiation safety monitoring equipment to handle alpha as well as gamma emitting isotopes. There are five major spectrometer systems available for spectrum measurements. These are shown in Table 3. Thus both neutron and gamma spectroscopy can be conducted. This equipment is used in conjunction with a Nuclear Data 4096 channel analyzer with tape transport for data readout.

Table 3 Spectrometer Systems

20 cm^3 Ge (Li) Gamma ray Spectrometer

7.62 x 7.62 cm NaI (Ti) Gamma ray Spectrometer

Ne -213 Organic liquid scintillation neutron Spectrometer

He -3 solid state sandwich neutron spectrometer

Thermoluminescence detection system

Several radioisotope sources are available to enable calibration of equipment and irradiation of science components. The gamma emitters available are given in Table 4. In addition, there are a number of polyenergetic sources. These include several SNAP-15A Pu^{238} metal heat sources, a PuBe neutron source, a Cf^{252} source, and an early version of a simulated PuO_2 source which was designed at JPL. This source was designed to reproduce the gamma-ray spectrum expected from a SNAP-27 fuel capsule.

Table 4 Standard Gamma Ray Calibration Sources

Radioisotope	Energy of Major γ-Ray (keV)
Am 241	59.5
Cd 109	87.7
Co 57	122 and 137
Hg 203	279.2
Cr 51	320.1
Sr 85	514
Cs 137	661.6
Mn 54	834.8
Zn 65	1115.4
Co 60	1173.2 and 1332.2
Na 22	1274.5
Ba 133	Many
Co 56	Many
Na 24	1370 and 2750
Co 57	122 and 137

GAMMA AND NEUTRON SPECTROSCOPY

An important aspect of the JPL radiation program is the ability to measure and interpret accurately the radiation fields from an RTG. In order to properly predict the response of an instrument to a polyenergetic source such as an RTG, the intensity and spectrum of the radiation must be measured quite accurately. In a previous section the equipment available to perform these measurements was discussed. The high resolution spectrometer, consisting of a Ge(Li) crystal having an active volume of 21.8 cm^3 and a resolution of about 3 keV at 1.33 MeV, has recently enabled a better definition of the radiation spectrum from a Pu^{238} heat source. This work was performed on a 1.5 W(t) SNAP 15A heat source by Reier and is documented in Ref. (3 and 8). The data given in Table 1 represents the latest measurements of the emission characteristics of Pu-238. An important outcome of this work was the development of a technique to accurately measure the concentration of Pu^{236} in a fuel capsule from the measurement of its emission characteristics. If a measurement is made of the absolute intensity of a transition of one of the daughter products of Pu^{236}, the amount of Pu^{236} in the fuel at the time the fuel was processed can be calculated. Since the Po^{212} - Tl^{208}

branching ratio is well known, an absolute measurement of the intensity of the radiation emitted during this decay (a 2.615 MeV photon is emitted for each decay) identifies the original amount of Pu^{236} present in the fuel. It is felt that by the use of this technique, a precision of 10% is easily obtainable with a sample that is several months old and has a nominal concentration of 1 ppm of Pu^{236}.

Another interesting problem which has been studied at JPL deals with interpretation of spectrum measurements. The experimentally determined spectrum of a given radiation source generally does not represent the true radiation characteristic of the source. This is mainly due to detector resolution and photon scattering within the crystal, resulting in partial energy deposition. To obtain the true radiation spectrum one employs some form of unfolding technique. Many codes are indicated in the literature for the unfolding of data obtained with a Na(I) crystal. However, until recently no such tool was available for the unfolding of the gamma-ray spectra continuum obtained with the high resolution lithium-drifted germanium gamma ray spectrometers. Such a tool is now available (Ref. 9) from work sponsored at the Jet Propulsion Laboratory. The laboratory now has available all of the necessary unfolding codes to interpret the data from gamma as well as neutron spectrometers.

DETERMINATION OF COMPONENT RESPONSE

The approach at JPL has not been merely to determine the response of science instruments to the mixed radiation field from a specific source. Instrument response is a function of both types and energy of the particle, and since the energy spectrum from any RTG depends on the geometry, materials of construction, and the age of the Pu^{238} fuel, it is more meaningful to measure this response with monoenergetic radiation sources. Seven isotopes are being used to perform these experiments. Table 5 gives the isotopes and their gamma emission energies. An extensive number of nuclear detectors which form the components of the most sensitive scientific instrument packages have been obtained for investigation. These devices are listed in Table 6.

Table 5 Monoenergetic Gamma Emitters Used for Component Response

Radioisotope	Energy (keV)
Hg 203	279
Sr 85	514
Cs 137	662
Mn 54	835
Zn 65	1115
Co 60	1173 and 1332
Na 22	1274
Na 24	2750

Table 6 Radiation detectors available for Component Response Studies

EON 6213 G-M Counter

Channeltrons (Bendix 4010, EMR)

Silicon Surface Barrier detectors

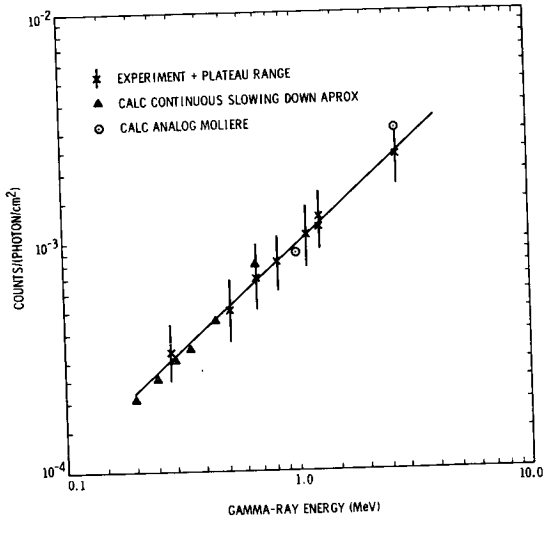
Silicon Lithium drifted detectors

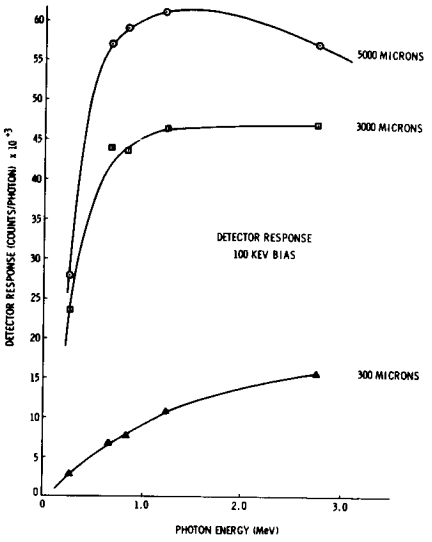
Photomultiplier tubes

Pilot B plastic scintillators

Cesium Iodide (Na) crystals

Two of these devices, the GM tube and solid state detectors, have been extensively characterized at JPL and the results documented in the open literature (Refs. 10, 11, 12). Figure 3 shows the experimental results obtained for a miniature Geiger-Mueller tube, while Figure 4 indicates some of the experimental results obtained with solid state detectors of various sizes. Primarily, these devices respond to the electrons that are generated by the gamma radiation in the structure material surrounding the sensitive regions of the detectors. Significantly, it was found that the atomic number and configuration of the surrounding structure had little to do with the magnitude of the response. For example lucite and aluminum were just as effective in producing spurious counts as was a very high atomic number material such as lead. Moreover, placing absorbers both in front and back of the detector did not alter the response significantly. Thus, it was concluded that, for engineering purposes, the maximum response of a detector can be effectively measured by conducting experiments in which a thin sheet of aluminum is placed immediately in front of the detector. The aluminum need only be of a thickness equivalent to the maximum range of an electron produced by the gamma ray in question.





As part of the JPL overall program we are not only measuring the response of devices to radiation but in addition have developed analytical models to predict response. By comparing the results with experiments we have been able to improve our models significantly. Such models enable us to predict the performance of devices which are of different size, or configuration than the unit which has been tested and also enables predictions of devices not available for experiments. Of more importance is the fact that there is a complete class of experiments which are extremely difficult to perform and for which analytical models are preferred. These are experiments to determine the response of devices to monoenergetic neutrons. A clean field of neutrons without accompanying gamma rays is not possible. Since detectors are generally more sensitive to gammas than to neutrons, an accurate understanding of the response to neutrons is very difficult. Of course time-of-flight techniques in which the gamma response is differentiated from the neutron response is possible but extremely expensive. Thus, at JPL, we have initiated an analytical program to determine the response of devices to neutrons. This will be accompanied with a low level experimental program to substantiate our model. Some initial work which has been accomplished to date in this area was reported by Taherzadeh at this conference (Ref. 14).

INSTRUMENT RESPONSE AND SHIELDING ANALYSIS

Once the spectrum of radiation impinging on an instrument from a polyenergetic source is established, it is possible from basic monoenergetic response data to determine the total response of an instrument. With this and a knowledge of allowable response levels, the required thickness of shield to reduce the response to a tolerable level is quickly determined.

The spurious count rate of a science instrument is determined from the expression

$$C = \sum_{i=1}^{20} \xi_i \cdot \eta_i \cdot S_i \cdot A$$

where

C is the total spurious counting rate (Counts/sec)

A is the sensitive area of the detector (cm^2)

S is the spectrum of radiation at the instrument (photons/cm^2 -sec)

N is the relative sensitvity to monoenergetic photons (counts/photon)

ξ is the relative attenuation of the shield (photons out/ photons in)

The calculations are typically done in 20 energy groups. With knowledge of the maximum allowable counting rate for a given instrument, the thickness of shield can be determined from the above expression. Numerous shielding studies have been conducted at JPL by Dore on various spacecraft configurations and reported in the literature (Ref. 13). Typical scientific packages which have been studied to date at JPL are shown in Table 7. The table indicates the type of sensors employed in these instruments.

Table 7 Typical Science Instruments

Experiment	Sensitive Detectors	Number	Sensitive Area	Thickness (in microns)
Charged particle telescope	Li-drifted S. S	1, 1, 2, 1	3.8 cm^2, 4.9 cm^2, 7.1 cm^2, 1.9 cm^2, 7.1 cm^2	500, 1500, 1000, 1000, 1000
Plasma probe	Channeltrons or PM's	40	1.2 cm^2	---
Trapped radiation experiment	PM tube Solid-state detectors (Totally depleted)	1 2 1	1 mm^2 500μ x 1000μ in diam 0.7853 mm^2	100 500 1000
Trapped radiation detector	G. M. tubes (EON 6213) Solid-state detector	3 1	1 cm^2 11 cm^2	--- 32μ
X-ray Telescope	Proportional counters	7	133 cm^2	---
UV Photometer	Channeltron (CEM 4010) Geiger (EON 6213)	1 1	1.2 cm^2 1.0 cm^2	--- ---

REFERENCES

1. P. J. Gingo and M. A. Dore, "Gamma Radiation Characteristics of Pluton-Dioxide Fuel," JPL Technical Report 32-1481, NASA.

2. M. A. Dore, "Gamma-ray Source Characteristics of PuO_2," Trans. Am. Nucl. Sec., 13, 537 (1970).

3. M. Reier, "Absolute Gamma Ray Intensity Measurements of a SNAP 15A Heat Source," Nuclear Science and Engineering (in press).

4. M. Taherzadeh, "Neutron Emission Characteristics of a PuO_2 Source," Trans. Am. Nucl. Soc., 13, 537 (1970).

5. T. M. Jordan, "Beta--A Monte Carlo Computer Program for Bremsstrahlung and Electron Transport Analysis," AFWL-TR-68-111, October, 1968.

6. M. Reier, "The Design of a Source to Simulate the Gamma-Ray Spectrum Emitted by a Radioisotope Thermo-electric Generator," Transactions of the National Symposium on Natural and Man-made Radiation in Space, March, 1971, (To Be Published).

7. H. Davis and E. Koprowski, "Nuclear Radiation Environment for Thermo-electric Outer Planet Spacecraft," "Transactions of the Natural and Man-made Radiation in Space, March, 1971, (To Be Published).

8. M. Reier, "Spectral Analysis of Gamma Radiation from a SNAP 15A Source," Trans. Am. Nucl. Soc., 12, 478 (1969).

9. J. J. Steyn, "Code Cugel--A Code to Unfold Ge(Li) Spectrometer Polyenergetic Gamma Photon Experimental Distributions," NUS-692.

10. R. Campbell, "The Response of Miniature G-M Tubes to Monoenergetic Gamma Radiation," Trans. Am. Nucl. Soc., 13, 533 (1970).

11. M. Reier, "The Response of a Shielded 300-Micron Silicon Detector to Gamma Rays," Trans. Am. Nucl. Soc., 13, 534 (1970).

12. T. D. Jones et al, "The Response of Selected Totally Depleted and Lithium-Drifted Silicon Detectors to Monoenergetic Gamma and Neutron Radiation," Trans, Am. Nucl. Soc., 13, 539 (1970).

13. M. A. Dore, E. L. Noon, "RTG/Radio-isotope Heater Shielding for Sensitive Science Instruments on Spacecraft," Trans. Am. Nucl. Soc., 13, 539 (1970).

14. M. Taherzadeh, "The Response of Solid State Detectors to Monoenergetic Neutrons Determined by the Use of the Monte Carlo Technique," Transactions at the National Symposium on Natural and Man made Radiation in Space," Mar., 1971, (To Be Published).