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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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ACTIVITIES OF THE RTG RADIATION TEST LABORATORY PROGRESS REPORT FOR THE PERIOD OF JULY 1 to DEC. 31, 1969

EM 342-101 January 1970

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NUCLEAR POWER SOURCES GROUP

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A. OBJECTIVES

The need for a solar-independent power source for future space missions led to the development of radioisotope thermoelectric generators (RTGs). One of the major problems in integrating such a device into spacecraft designs is the compatibility of the inherent radiation field from the radioisotope power source with the space science experiments and other radiation sensitive subsystems. To investigate this interface problem, JPL has created an RTG Radiation Test Laboratory and has embarked on an experimental program to study the RTG radiation field and its interaction with susceptible spacecraft components. The test objectives of this experimental program include (1) the determination of both the neutron and gamma-ray source radiation characteristics in both energy and intensity, (2) determination of the level of interference from this mixed radiation field with scientific instruments and spacecraft subsystems and to delineate how this interference varies according to radiation component and energy of that component, (3) determination of methods for reducing the interference with sensitive components, (4) investigation of radiation damage that may occur during long term missions.

B. MAJOR ACCOMPLISHMENTS THIS PERIOD

(1) The Safety Analysis Report for the RTG Radiation Test Lab receipt of SNAP-19 or 27 fuel capsule assemblies has been written and has received JPL approval.

(2) The gamma-ray spectrum from a SNAP-27 fuel capsule assembly has been measured with both a calibrated Ge(Li) solid state spectrometer and with a 3" x 3" NaI(Tl) scintillation spectrometer.

(3) Data analysis has been completed for the gamma-ray spectrum measurements of a SNAP-15A heat source using a Ge(Li) spectrometer. This has lead to a new technique for determining Pu-236 impurity concentrations.

C. PROGRESS DURING REPORT PERIOD

1. RTG Radiation Test Laboratory (Facility Health and Safety, etc.)

The Safety Analysis Report (EM 342-94) for the use of SNAP-19 or SNAP-27 fuel capsules in the laboratory has been written and has received all necessary JPL approval. Copies have been printed and forwarded to the AEC Albuquerque Operations Office.

A decision has been made to receive the SNAP-27 fuel capsule assembly under a no cost contract with the AEC rather than through the AEC-NASA interagency agreement. It is anticipated that the final arrangements for this contract will be worked out during the next quarter. It is at this time that we should expect final approval of the Standard Operating Procedures and Safety Analysis Report.

As a result of a NASA fire inspection all wooden work benches were removed from the laboratory and replaced by equivalent metal furniture.

2. Radiation Experiments and Data Analysis

a) Radiation Sources

1) The two Am-241 gamma-ray sources have been received and make complete the set of gamma-ray calibration sources with intensities traceable to NBS standards.

2) A 5 Curie PuBe neutron source has been received on lab and will be used to calibrate health physics neutron monitoring equipment as well as act as a standard for the neutron spectrometer systems.

3) Simulated PuO_2 Source. The design of this source was discussed in detail in the previous quarterly report. Four sources have been ordered in the quantity required to simulate a 1575 watt (thermal) heat source with 5 year old fuel and all of these sources have been received. Unfortunately the Th-228, which mocks up the decay of the Pu-236 impurity, was received in an amount smaller by a factor of about 5 than that requested. The three other sources, Ba-133, Cs-137 and Z-65 can simulate the PuO_2 fuel spectrum at the time of processing. Depleted U-238 and lead plates have been fabricated to mock up the self shielding of fuel and shielding of the capsule.

b) NE-213 Neutron Spectrometer System. The NE-213 liquid organic scintillation spectrometer for neutrons and its associated electronic components have been sent to Battelle Northwest Laboratories for calibration. Two different volumes of encapsulated liquid organic were sent. One was 1-1/2 inch in diameter, the other 2 inches in diameter and both 0.4 inches thick. The details of the calibration may be found in section 5 - Battelle Northwest Laboratories Contract.

c) Spectrum Measurements of SNAP-15A Heat Source. The gamma-ray data from the SNAP-15A source have been completely analyzed. All of the corrections to the data have been applied and the errors have been calculated. These corrections included (a) detector efficiency (b) source to detector distance, (c) source container attenuation and (d) source self absorption. In general, the intensities of the unattenuated lines are in excellent agreement with the published results on Tl^{208}, Pb^{212}, and Bi^{212}, all daughter products resulting from the decay of the impurity, Pu^{236}. It is felt that the Pu^{238} data represent a significant improvement over previously published measurements. The raw spectra measurements are shown in Figures 1 through 7 and the reduced data shown in Tables 1 through 5. The details of the experimental work, data analysis and results will be presented in full in a technical report to be written next quarter for publication. This material was presented at the winter meeting of the American Nuclear Society (see V - reports).

d) New Technique for Pu Impurity Concentrations. The gamma-ray measurements of the SNAP-15A heat source reported above have led to a new technique for the determination of the Pu-236 impurity at the time of processing. The intensity of the gamma rays resulting from Th^{228} decay may be used to calculate the amount of Pu^{236} originally in the sample if we know when it was processed. The 2.615 mev line was used since its intensity (100% of Tl^{208} decays) and the α, β branching ratio of Bi^{212} appear to be very well established. In addition, the source self-shielding corrections are smallest for that line. The value obtained was 1.79 ± 0.07 ppm of Pu^{236} in the fuel at the time of processing. This agrees with the estimate of 1 to 2 ppm by Mound Laboratory. Using this technique it is felt that a Pu^{236} concentration in the 1 to 2 ppm

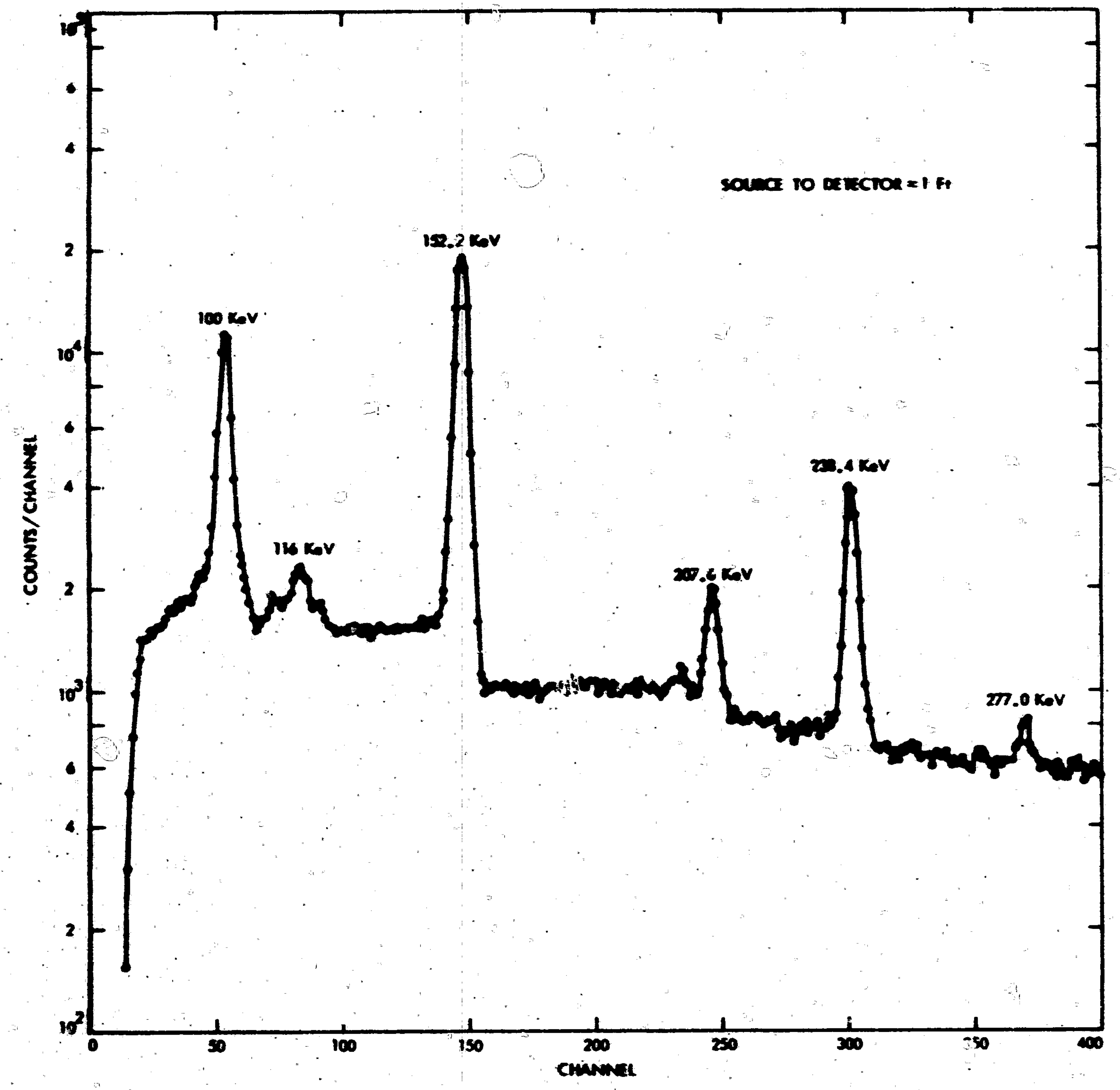

Figure 1. SNAP 15A Gamma Ray Spectrum, Run 59

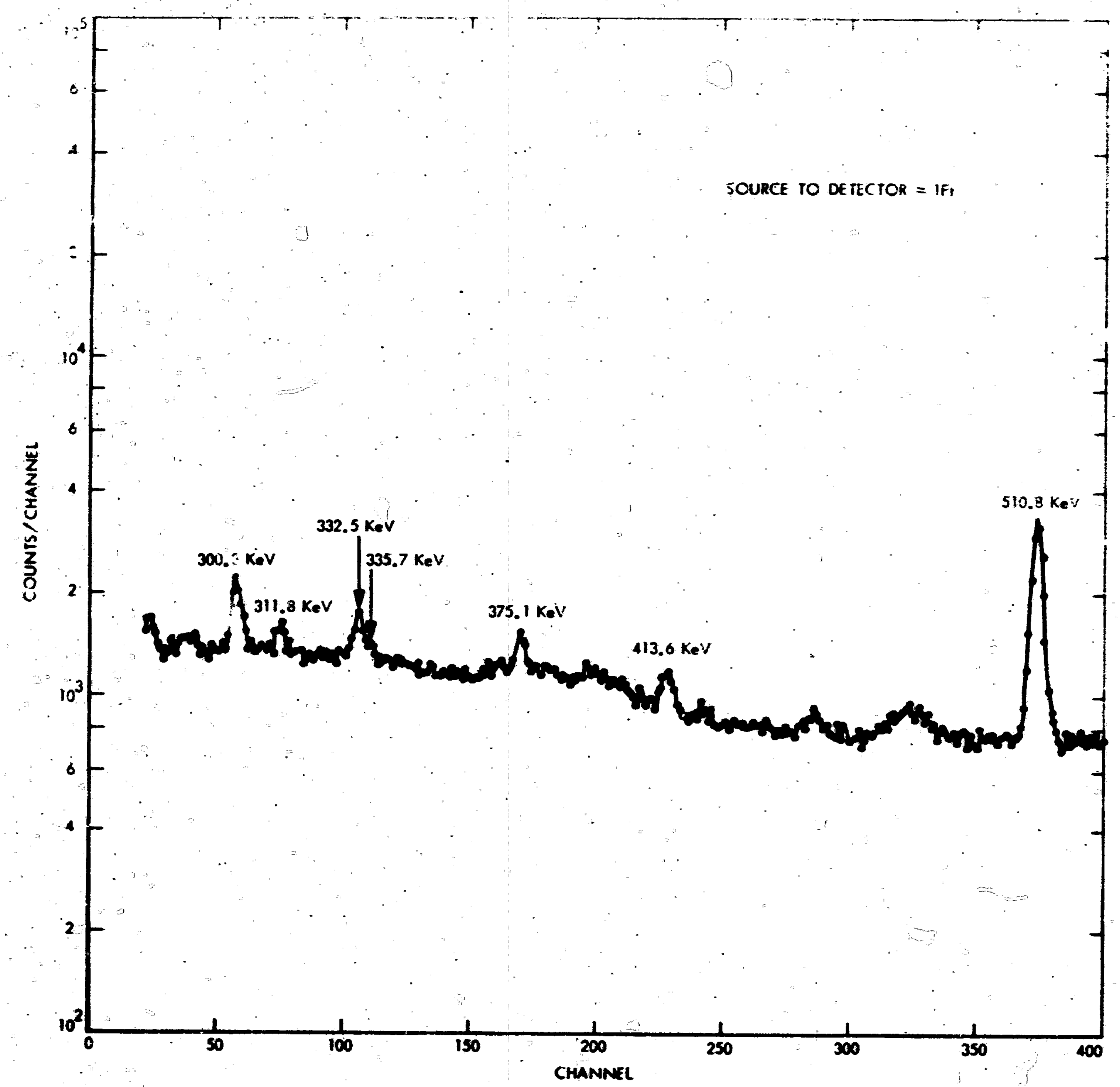

Figure 2. SNAP 15A Gamma Ray Spectrum, Run 60

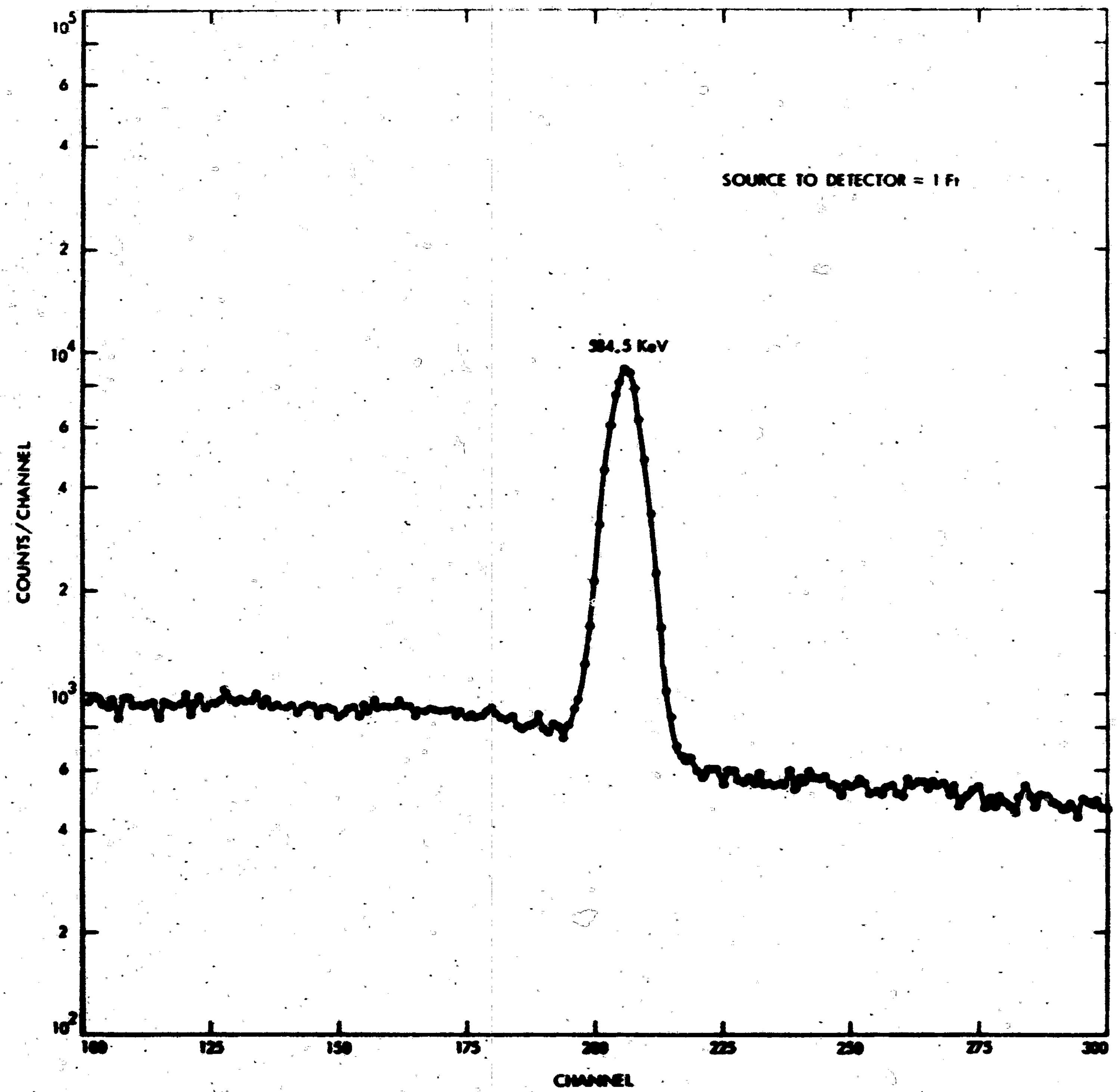

Figure 3. SNAP 15A Gamma Ray Spectrum, Run 61

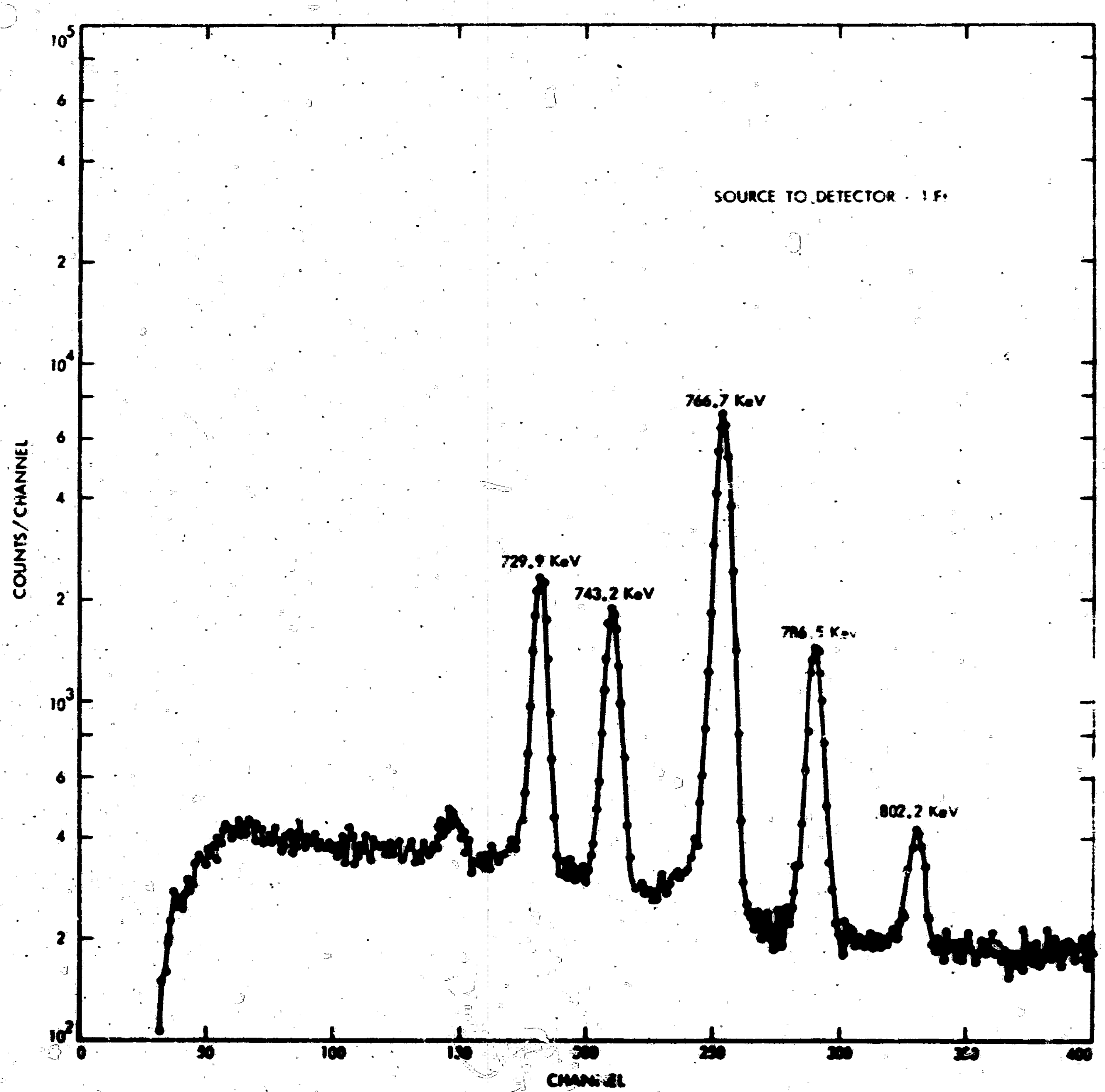

Figure 4. SNAP 15A Gamma Ray Spectrum, Run 62

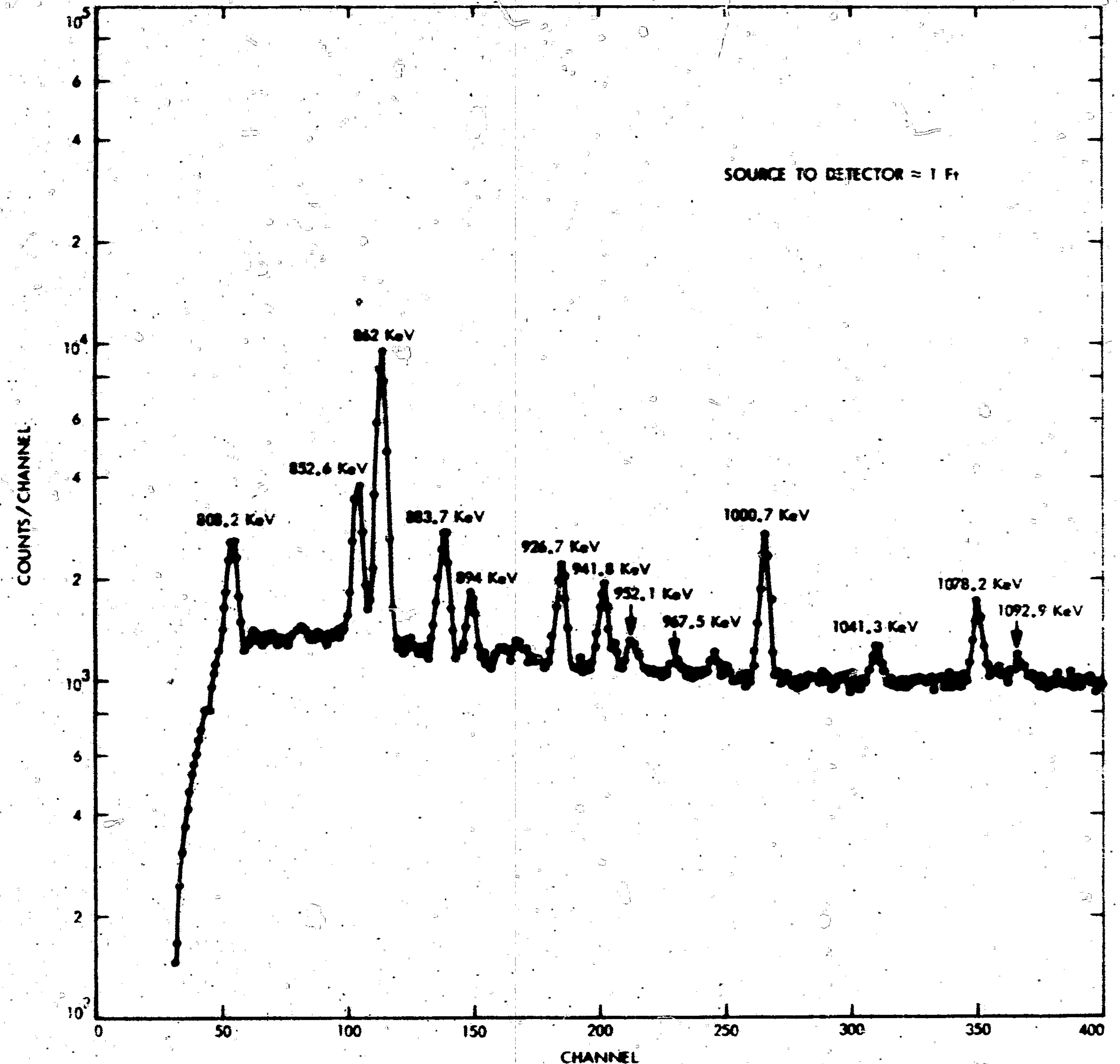

Figure 5. SNAP 15A Gamma Ray Spectrum, Run 66

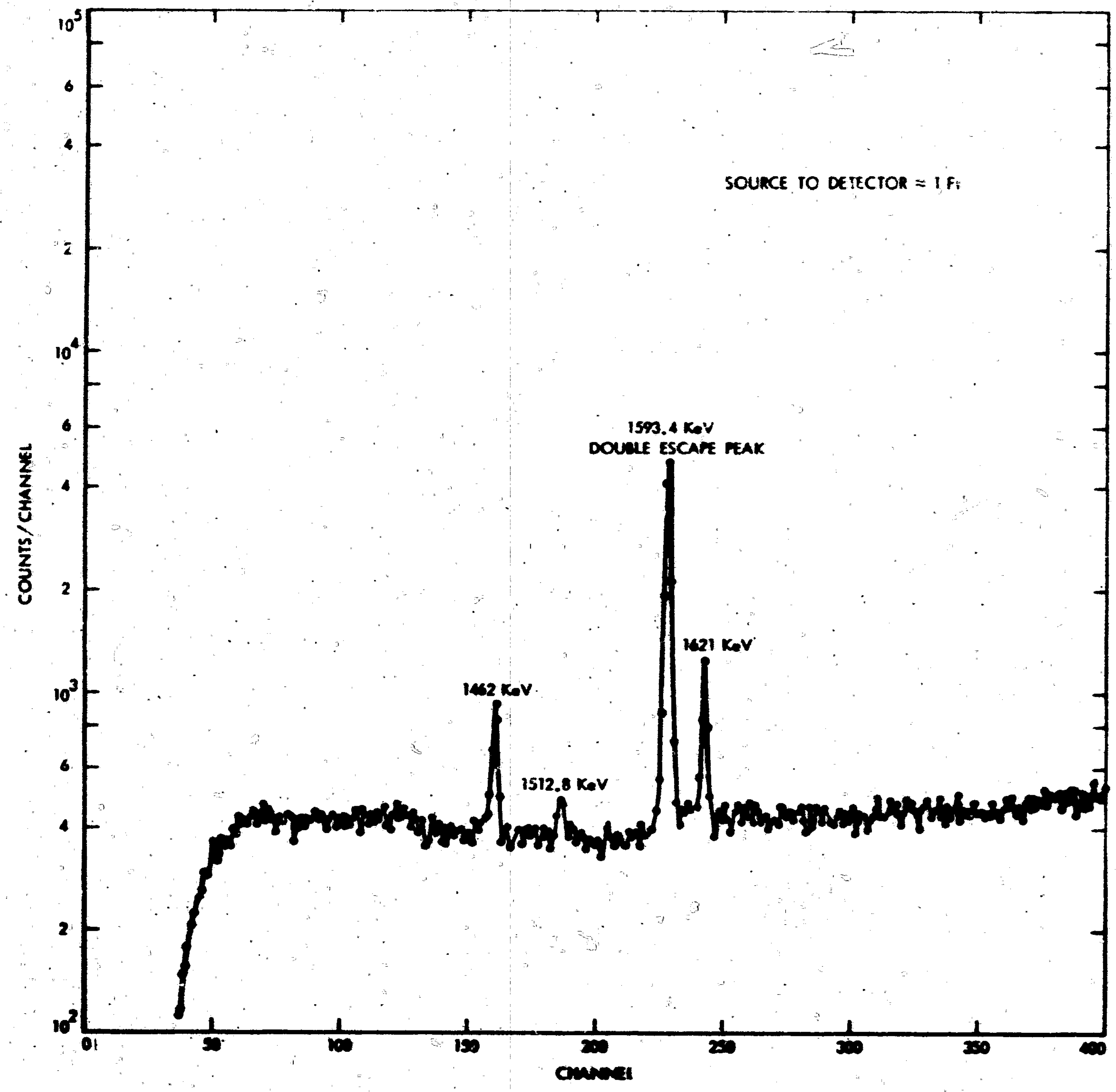

Figure 6. SNAP 15A Gamma Ray Spectrum, Run 64

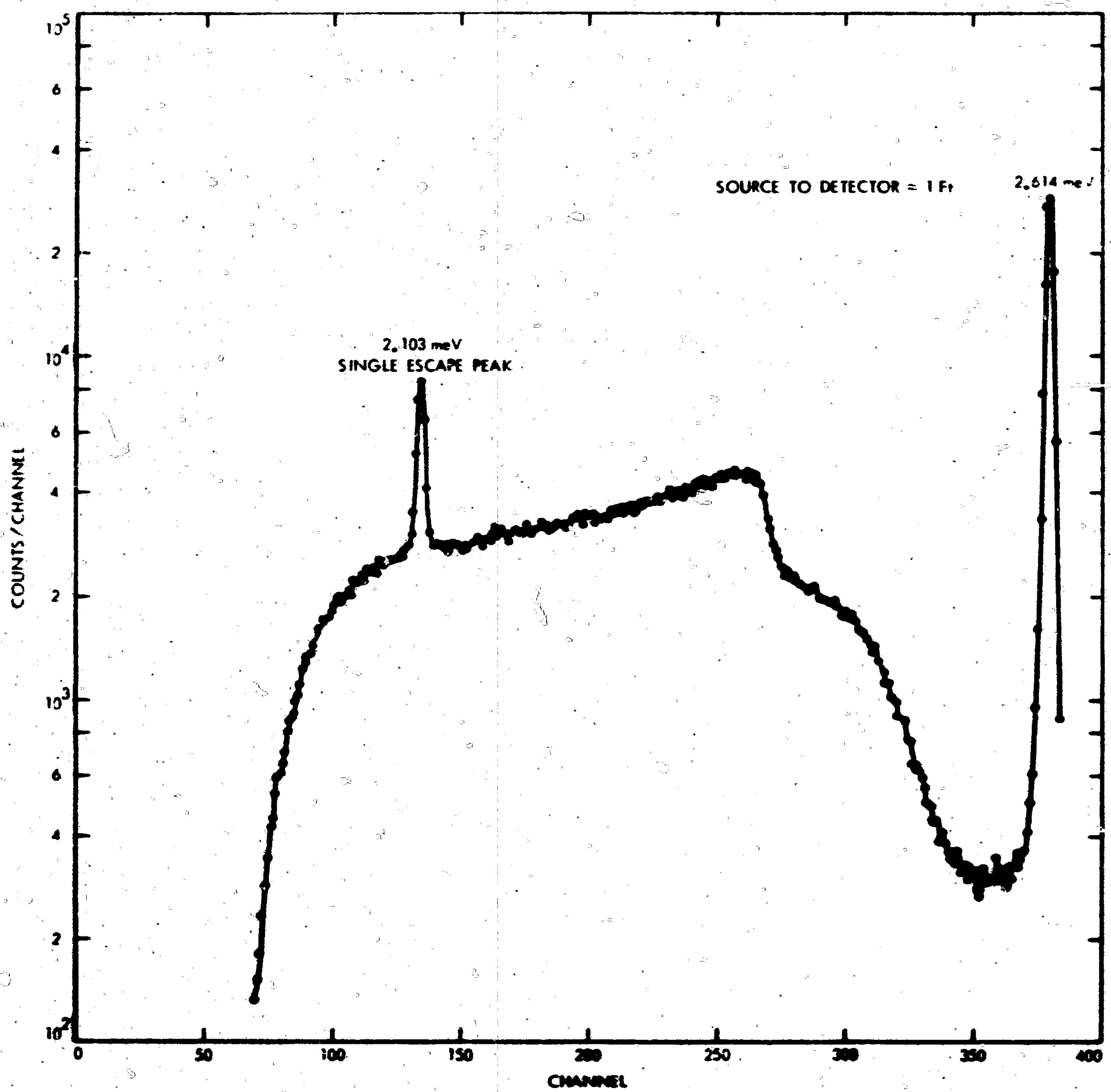

Figure 7. SNAP 15A Gamma Ray Spectrum, Run 67

Table 1. Photons per Second Emitted From SNAP-15A Capsule

Gamma-ray Energy (keV)	Photons/sec x 10^{-4}	Gamma-ray Energy (keV)	Photons/sec x 10^{-4}
116.0	0.516	808.2	0.898
152.2	24.2	852.6	1.526
207.6	2.48	861.4	4.546
238.4	8.56	883.7	1.201
277.0	0.521	893.9	0.385
300.3	1.091	904.9	0.0696
311.8	0.361	911.2	0.102
332.5	0.517	926.7	0.691
335.7	0.129	941.8	0.567
375.1	0.492	952.1	0.175
413.6	0.843	967.5	0.119
510.8	8.23	1000.7	1.095
584.5	23.7	1041.3	0.201
729.9	6.10	1078.2	0.528
743.2	5.35	1092.9	0.188
766.7	23.2	1462.	1.678
786.5	4.39	1512.8	0.498
807.0	0.695	1621.	2.04
		2164.	49.2

Table 2. Pu-238 Gamma-Ray Energies and Intensities

E (kev)	Photons/Disintegration	Matlack et al[a]	Ratio (This work/ Matlack)
152.2	seen[b]	seen	
207.6	seen[b]	seen	
743.2	$(6.39 \pm 0.21) \times 10^{-8}$	4.5×10^{-8}	1.42
766.7[c]	$(2.69 \pm 0.08) \times 10^{-7}$	2.0×10^{-7}	1.35
786.5[d]	$(5.02 \pm 0.16) \times 10^{-8}$	2.8×10^{-8}	1.79
808.2	$(1.009 \pm 0.064) \times 10^{-8}$	6.0×10^{-9}	1.68
852.6	$(1.66 \pm 0.07) \times 10^{-8}$	1.2×10^{-8}	1.38
883.7	$(1.281 \pm 0.048) \times 10^{-8}$	7.4×10^{-9}	1.73
904.9	$(7.32 \pm 2.15) \times 10^{-10}$		
926.7	$(7.16 \pm 0.36) \times 10^{-9}$	5.0×10^{-9}	1.43
941.8	$(5.85 \pm 0.25) \times 10^{-9}$	6.0×10^{-9}	0.98
1000.7	$(1.092 \pm 0.044) \times 10^{-8}$	8.5×10^{-9}	1.28
1041.3	$(1.99 \pm 0.22) \times 10^{-9}$	2.0×10^{-9}	1.00
1085.1		1.0×10^{-9}	
1462.0	$(1.465 \pm 0.121) \times 10^{-8}$		

a) Matlock, G. M. et al. "Neutron and Gamma Radiation from Pu-238," Amer. Nucl. Soc. National Meeting, 10-15 Nov, 1968.

b) Source shielding corrections are too high to justify reporting intensity.

c) Tl^{208} has a line at 763 kev.

d) Bi^{212} has a line at 768 kev also.

Table 3. Tl-208 Gamma-Ray Energies and Intensities

E (kev)	Intensity (%)		
	Present Expt	Schupp et al[a]	Lederer[b]
277	9.8 ± 0.7	8.6	7
486		0.1 ± 0.1	0.1
510.8	36.6 ± 1.9[c]	25.3 ± 1.2	23
584.5	89.3 ± 4.4	85.1 ± 4.0	86
763[d]		3.4 ± 0.2	2
861.4	12.5 ± 0.6	14.2 ± 0.6	12
1093	0.46 ± 0.11	0.7 ± 0.1	0.6
2615	100	100	100

a) G. Schupp et al. Phys. Rev 120, 189 (1960).

b) C. M. Lederer et al. Table of Isotopes, 6th Ed. John Wiley & Sons, 1967.

c) This value is high because of the production of annihilation radiation in the source itself.

d) Not resolved from the 766 kev line in Pu^{238}.

level can be measured with an accuracy of better than 10% even if the fuel is only several months old since the time of processing. This capability is particularly important in a flight program where accurate knowledge of the impurity content of the delivered fuel must be known to assess its long term radiation characteristics.

e. Radiation Interference Measurements

1) The response of a 300 micron fully-depleted silicon detector to gamma rays has been measured using Sr^{85}, Mn^{54}, and Co^{60} sources. Because the detector is virtually transparent to gamma rays, but black to

Table 4. Bi-212 Gamma-Ray Energies and Intensities

E (kev)	Intensity (%)	
	Present Expt[a]	Schupp et al[b]
729.9	10.5 ± 0.5	11.1 ± 0.7
785[c]		1.7 ± 0.26
893.9	0.58 ± 0.03	0.66 ± 0.07
952.1	0.25 ± 0.03	0.16 ± 0.04
1078.2	0.73 ± 0.05	0.99 ± 0.08
1512.8	0.61 ± 0.12	0.49 ± 0.05
1612	2.47 ± 0.21	2.80 ± 0.20
1800		0.17 ± 0.03

a) Compared with intensity of 2615 kev line of Tl^{208} corrected for Bi^{212} α, β branching ratio.

b) G. Schupp et al. Phys. Rev. 120, 189 (1960).

c) Pu^{238} also has a line at 786 kev.

electrons, it is very difficult to make a clean measurement. The creation of electrons in the surroundings may have a very significant effect. Monte Carlo calculations performed by ART Associates under contract to JPL show that even the 0.010 in. mylar coating over the source cannot be neglected. The internal conversion electrons will very often be more significant than the gamma rays even when the internal conversion coefficient (1/c) is as low as 0.01. Table VI shows the experimental results obtained. The values must be treated as upper limits for reasons expressed above. A parallel analytical effort has been undertaken by ART Associates mocking up the entire geometry including material in the vicinity of the source and detector which might cause spurious increases in the efficiency. The gamma interaction is treated by Monte Carlo techniques. The electron energy deposition in the crystal is

Table 5. Pb-212 Gamma-Ray Energies and Intensities

	Intensity (%)		
E(kev)	Present Expt[a]	Emery et al[b]	Lederer[c]
116.0	seen		0.7
176.7			0.2
238.4	101 ± 6	47 ± 9	47.0
300.3	5.5 ± 0.3	3.6 ± 0.5	3.2
415.2			0.16

a) Compared with intensity of 2615 kev line of Tl^{208} corrected for Bi^{212} α, β branching ratio.

b) G. T. Emery and W. R. Kane, Phys, Rev. 118, 755 (1960).

c) C. M. Lederer et al Table of Isotopes, 6th Ed. John Wiley & Sons, 1967.

Table 6. Efficiency of 300 Micron Silicon Detector to Gamma Rays

E(MeV)	e/γ	Bias (MeV)	Counts From All Effects/ 100 Photons
0.513	0.007	0.05	3.80
		0.1	3.02
		0.2	1.72
0.835	0.00025	0.05	2.54
		0.1	1.94
		0.2	0.97
1.25	0.0002	0.05	2.75
		0.1	2.06
		0.2	0.95

treated by theoretical energy loss equations supplemented by a modified Monte Carlo approach to account for the tortuous path of an electron during the slowing down process. Both the analytic and experimental effort will continue during the coming quarter.

2) EON-6213 GM Tube. The response of an EON-6213 Geiger-Müller tube has been determined for monoenergetic gamma-rays at six energies. Counting rates will be related to the absolute efficiency of the G-M tube and compared to analytic calculations next quarter.

3) Simulated Source Measurements. Lacking the appropriate amount of Th-228 isotope to complete the simulated PUO_2 source, the 3 available sources were used to simulate a source at the time of fuel processing when no Th has built up. The response of a 1" x 1" and 3" x 3" NaI crystal and a 1 mm and 10 mm Pilot B scintillator to this "zero-year" source has been measured. In addition, the response of these four detectors to monoenergetic gamma rays from 166 Kev to about 1.1 Mev was measured. The analysis of the NaI data will proceed when the CUPED spectrum unfolding code is received from NUS and made operable on our computing system.

3. Interfaces With Other Facilities

a) JPL negotiated, though Ames Research Center, an arrangement whereby we were able to measure the gamma-ray spectra emitted by the SNAP-27 fuel capsule assembly now on loan to TRW Systems. Detailed measurements were made using our own calibrated Ge(Li) solid state spectrometer system (see last quarter report) and a limited number of runs were made using the 3" by 3" NaI (Tl) scintillation spectrometer system. These latter measurements were made both perpendicular to and along the axis of the fuel capsule assembly in order to investigate the increased attenuation along the axis due to the increased self absorption in this direction. Data were obtained in tabular form and will be presented in graphical form next quarter.

b) We had hoped to receive from Goddard Space Flight Center an updated version of the data analysis code CUBED called CUPED (see previous quarterly). This new code will allow the analysis of a considerable number of gamma-ray peaks superimposed on a continuum as obtained by a NaI (Tl) scintillation spectrometer system. Unfortunately the code has required some additional modifications and will now not be available for use until next quarter.

4. Analytic Effort. In addition to the analytic work by ART Associates referred to in C. 2. e, a study was performed to determine the influence of both fuel age and Pu-236 concentration on shielding requirements for sensitive interplanetary radiation detectors.

In order to accurately determine such shielding requirements, a five part program was needed. (1) One must first know accurately the source spectrum from the plutonium, including Pu-238, radioactive impurity isotopes, and decay daughters (as for the Pu-236 considered in detail here), the latter contributions being highly dependent on the elapsed time since chemical separation of the fuel. (2) Secondary sources of radiation must be known, such as the contributions from (α, n) reactions with O-18. This all implies detailed knowledge of the chemical and isotopic composition of the basic fuel. (3) Given this, one can then utilize various existing computer codes to determine gamma fluxes external to a capsule of some given geometry, including the generator which surrounds the capsule. (4) Then for a given set of radiation detectors, it is necessary to know for each the effective surface area, relative spacial orientation, separation distance from the RTG's, and energy dependent response to gamma radiation in order to find the spurious count rate of each as a function of a given incident spectrum. (5) The final part of this shielding program is to then determine the minimum necessary shield area (assuming spot shields as is done here), and relative attenuation of the chosen shield material as a function of thickness and gamma energy, including downscatter in energy and the contributions from neutron induced gammas.

A typical compliment of science experiments was selected for this investigation. These include: (1) a LEPEDEA* experiment, containing one channeltron electron multiplier CEM-4010 and one Geiger-Müller tube EON-6213; (2) a UV photometer, containing one channeltron and one G-M tube; (3) a trapped radiation detector, containing three G-M tubes and one solid state detector (12 mm^2 x 31 μm); and, (4) a cosmic ray telescope, containing a single solid state detector (5.7 cm^2 x 200 μm).

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*Low Energy Proton and Electron Differential Energy Analyzer

The analysis assumed a 1575 W(th) cylindrical fuel capsule, with the sensitive instruments located 10 feet distant on the capsule mid-plane. Gamma ray spectra for the Pu-238 fuel capsule were then determined, using both Boltzmann transport and point kernel integration computer codes, for 20 energy groups between 1 KeV and 7 MeV. These spectra varied as a function of fuel age and the relative concentration of Pu-236. Coupling this data with the energy dependent response of each of the detectors allowed the spurious count rate of each of the unshielded instruments to be determined. By establishing acceptable limits for spurious count rates, minimum spot shield thicknesses and weights as a function of age and Pu-236 content are then calculated.

For 18 year-old fuel (worst case), results for total tungsten shield weight for the science package indicate that, below about 2 ppm, shield weight departs significantly from being logrithmatic with Pu-236 concentration, tending towards a constant value of about 3 pounds. This suggests that a substantial reduction in shield weight does not result from cleaner fuel than the 1.2 ppm currently available. However, a considerable weight penalty does result from using liquid metal fast breeder reactor produced fuel, with weights in excess of 20 pounds being required.

Tungsten shield thicknesses for the individual detectors behave similarly, with more than 6 inches required in some cases for 500 ppm fuel, a highly undesirable situation from the standpoint of spacecraft geometry considerations.

The results of this study have been reported in an engineering memo, reference 2, and presented at the Winter meeting of the A.N.S.

5. Battelle-Northwest Laboratories Contract. Most of the work accomplished during this period of the contract was involved in procurement of the specified radiation detectors, fabrication of the depleted uranium shields, and preliminary check out of equipment and systems.

Immediately after receipt of the contract, specifications were written and bids requested for two types of silicon solid state detectors; 1) totally depleted surface barrier detectors, and 2) lithium drifted detectors. Geiger-Muller counters, type 6213, and electron multipliers type CEM-4010 were purchased on a no substitution basis. The totally depleted surface barrier detectors were specified with areas of 200 mm^2 and depletion depths of 100, 300, 500, and 1000 microns. One additional detector was ordered with an area of 50 mm^2 and a depletion depth of 30 microns. Lithium drifted silicon detectors were specified with surface areas of 200 m^2 and drifted depths of 1 mm, 2 mm, 3 mm, and 5 mm. The totally depleted surface barrier detectors were ordered from Nuclear Diodes, Inc., Prairie View, Illinois, on the basis of their low bid. The lithium drifted silicon detectors were ordered from Nuclear Semiconductors, Inc., San Carlos, California, also on the basis of their low bid.

Depleted uranium shields were designed and fabrication completed for use with the type 6213 Geiger-Muller counters. The shields were cylindrical with thicknesses of 0.050, 0.100, 0.200, 0.500, and 1.000 inches and are split in half to allow measurements of response with 180° shielding.

After receipt of the Geiger-Muller counters, special connectors were fabricated to furnish high voltage to the counters. A special junction box was designed and fabricated for proper routing of the signal and high voltage to the counters. The counters were connected and given a preliminary check out using ^{241}Am and ^{137}Cs sources.

Before continuing with the photon response studies which were requested to be conducted prior to the neutron response studies, it was necessary to measure the spectra emitted by the K-fluorescence and filtered X-ray sources at Battelle-Northwest. Some of these sources will be needed for the low energy photon response studies.

In Figures 8 through 10 the energy spectra for K-fluorescence sources chosen for further use with average energies of 16, 58, and 100 keV are illustrated. The data are presented on a logarithmic scale so the background and X-ray continuum are emphasized in relation to the characteristic peaks. For most of these sources the characteristic peaks are a factor of 30 to 100 larger than the background level. The spectra shown have not been corrected for the efficiency of the lithium drifted detector used to make the measurements. The lithium drifted germanium detector, Ge(Li), has a resolution of about 400 eV measured for 6.4 keV photons through an entrance window of 0.010 inches beryllium. The volume of the detector is 50 mm^3.

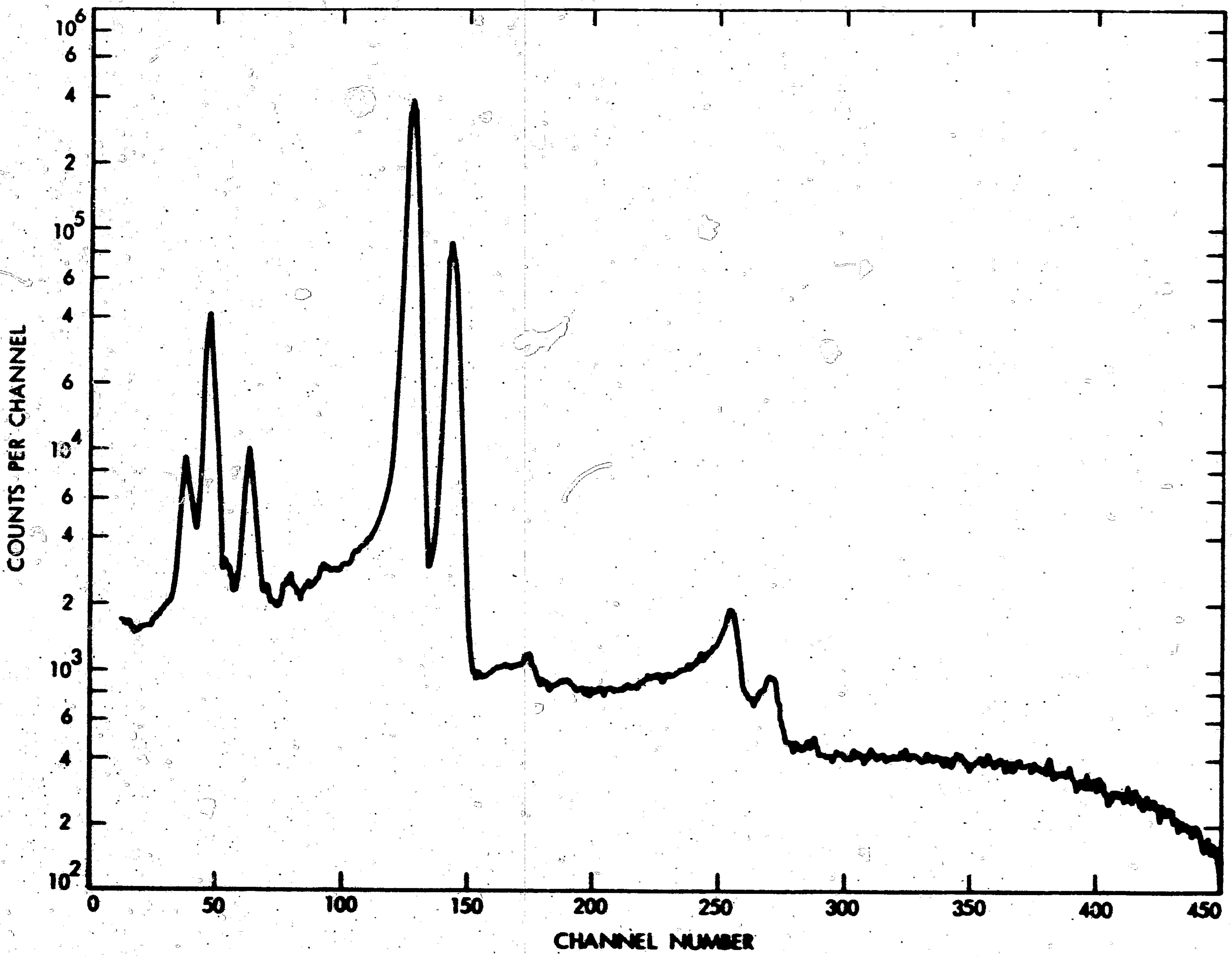

Figure 8. K-fluorescence X-ray Spectrum 16 keV

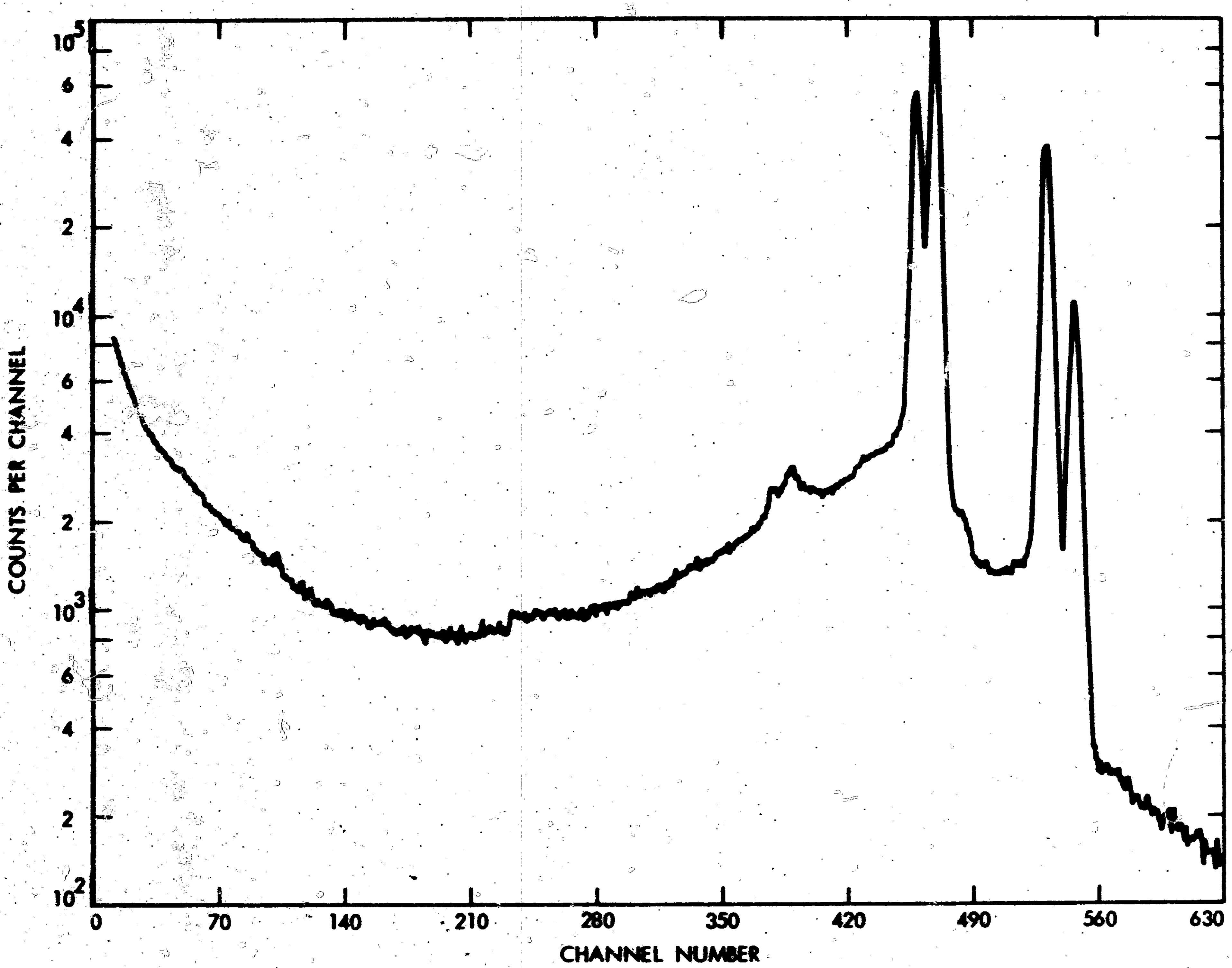

Figure 9. K-fluorescence X-ray Spectrum 58 keV

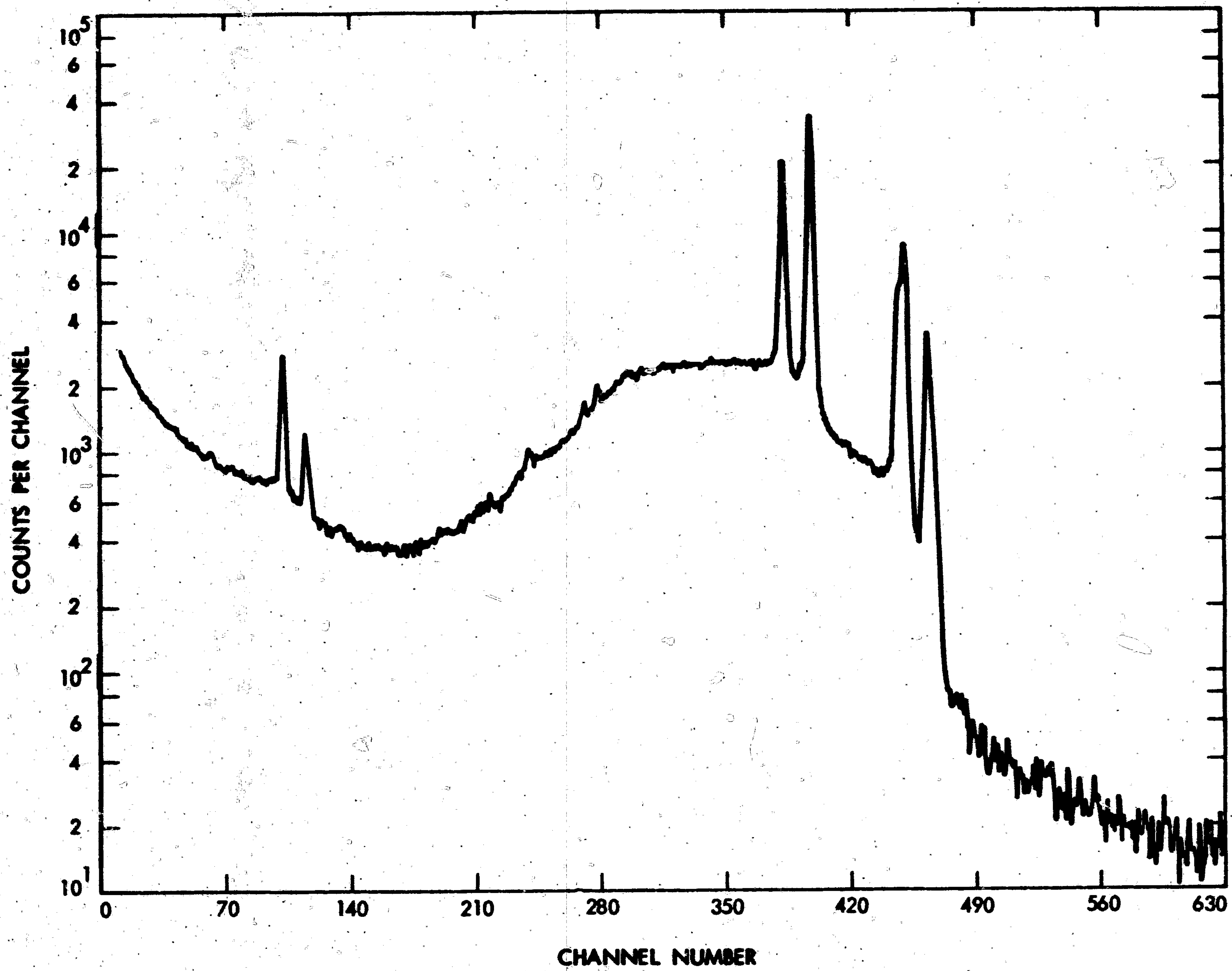

Figure 10. K-fluorescence X-ray Spectrum 100 keV

It should be noted in the case of the K-fluorescence X-rays that the spectra show evidence of summing in the detector by the presence of small peaks at twice the energy of the main characteristic peaks. Some peaks at about 10 keV less than the main characteristic are due to the escape of the germanium X-rays from the detector. For Figures 8 and 9 the energy calibration is 0.119 keV per channel. For Figure 10 the calibration is 0.238 keV per channel.

The special NE-213 liquid organic scintillation neutron spectrometer supplied by JPL for check out and calibration with monoenergetic neutrons was assembled. Proper operation of the pulse shape discriminator was achieved with good separation between gate signals generated by neutron and gamma events. In order to use the spectrometer to measure an incident neutron spectrum the efficiency of the pulse shape discriminator as a function of neutron energy must be known. To determine the absolute efficiency of the discriminator as a function of neutron energy, exposures were made to monoenergetic neutrons with energies of 1.1, 1.5, 2.7, 3.6, 4.1, 4.3, and 5.0 MeV produced by the Van de Graaff positive ion accelerator. The results of these exposures are shown in Table 7.

Table 7. Absolute Efficiency of Pulse Shape Discriminator

E(MeV)	Neutron Events	Fluence n/cm^2	Events/(Fluence) x 10^5
1.1	5,809	5.35×10^5	1.08×10^3
1.5	83,334	5.57×10^5	1.49×10^4
2.7	115,552	6.79×10^5	1.71×10^4
3.6	113,210	4.91×10^5	2.29×10^4
4.1	107,203	4.79×10^5	2.24×10^4
4.3	100,430	4.70×10^5	2.14×10^4
5.0	327,147	1.71×10^5	1.91×10^4

The energy of the neutrons is determined by the energy of the bombarding particle used. In these measurements all exposures were with a deuteron beam and either a carbon or deuterium target. The number of neutron events was determined by integrating the total number of neutron gate signals that occurred during the exposure. Fluence measurements were conducted with the precision long counter at an appropriate angle and distance from the accelerator target. The number of neutron events per 10^5 n/cm^2 is shown to illustrate the absolute efficiency of the discriminator as a function of neutron energy. The efficiency increases from 1.1 MeV to about 3.6 MeV and then remains essentially constant from 3.6 MeV to 5.0 MeV.

The problem of achieving proper timing between the neutron gate signals and the linear signal for spectrum measurements has not been solved. Several double delay line amplifiers have been tried without success. JPL has sent to Battelle a delay amplifier which should now solve this problem.

D. PLANNED ACTIVITIES NEXT QUARTER

1. RTG Radiation Test Laboratory (Facilities, Health and Safety, etc.)

Meetings will be held with AEC/ALO personnel to finalize the no cost contract for use of a SNAP-27 fuel capsule assembly. This may include a survey of the facility by AEC/ALO safety personnel although this may be delayed until just prior to the actual receipt of a fuel capsule.

2. Radiation Experiments and Data Analysis

a) Final results on the EON-6213 GM tube and the solid state silicon detector will be reported.

b) Analysis of the gamma-ray spectrum from the SNAP-27 fuel capsule assembly will begin.

c) The appropriate amount of Th-228 isotope for the simulated PuO_2 source will be obtained and measurements will be made of the emitted spectra and of the response of instruments to this radiation.

3. Interfaces With Other Facilities

Communications with Goddard Space Flight Center will continue for the purpose of exchanging information and in particular data reduction codes which may prove useful to the other facility.

4. Analytic Effort

A report will be written which summarizes the Monte Carlo effort in instrument component modeling and radiation response. A model will also be established for the radiation absorption and scattering that will take place in a thermoelectric generator surrounding the fuel capsule assembly.

Radiation levels and spectra from small 15 watt PuO_2 heat sources will be investigated.

5. Battelle-Northwest Laboratories Contract

The procurement of overdue instrument components should be completed so that the gamma-ray interference measurements may be made. It is felt that the majority of these should be completed by next quarter.

Calibration of the NE-213 liquid organic scintillators should be completed.

E. REPORTS PUBLISHED THIS PERIOD

1. "Gamma Radiation Characteristics of Plutonium Dioxide Fuel", Gingo, Dore, E.M. 342-84.
2. "Effect of Pu-236 on Shielding Requirements for RTG Spacecraft Experiments", Dore, E.M. 342-98.
3. "RTG Radiation Test Laboratory", Campbell, Space Programs Summary 37-59 Vol. III.
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