Identification and Control of Spacecraft Radiation Sources of Interference to X-Ray and Gamma-Ray Experiments*

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Apollo 15 and 16 will carry instruments for the purpose of measuring x-ray and gamma ray fluxes from the lunar surface and in cis-lunar space. The intensity levels expected are low over most of the energy range of interest, requiring that background contributions be minimized. The radiation sources on Apollo have been determined and their interference with these instruments evaluated. The results have been used as a basis for dealing with this problem and for recommendations applicable to future manned and unmanned missions.

X-ray spectrometers and gamma ray spectrometers can be used to measure fluxes of x-rays and gamma rays which originate at the surface of large objects in the solar system with little or no atmosphere such as the Moon and Mars. The gamma rays arise from two sources:

1. The radioactive decay of certain isotopes whose half-lives are comparable to the time since nucleosynthesis, principally K-40, Th-232 and U-238 and the daughter products of the last two.
2. The interaction of cosmic rays with the surface material in the form of a radiative and nucleonic cascade which distributes the energy of the cosmic ray over numbers of target nuclei.

In contrast, the dominant cause of observable x-rays to distances beyond the orbit of Mars is the Sun, whether quiet or active, which emits x-rays which will induce secondary fluorescent emission in the object they strike. The gamma ray and x-ray fluxes from the surface of the object will both contain line radiation characteristic of the originating element or isotope as well as a continuum energy distribution. The line radiation therefore contains compositional information.

Fluxes of x-rays and gamma rays also arise as the result of energetic physical interactions within the galaxy and beyond. The measurement of these fluxes has become the basis of x-ray and gamma ray astronomy. Their properties of location, intensity, line and continuum energy distribution, time variability and correlation with emissions at longer wavelengths promise to provide much information on the current state and past evolutionary processes of the universe.

Observations of celestial x-rays and gamma rays are most suitably made from satellites to avoid the effects of the Earth's atmospheric attenuation and to increase the experiment time. Observations of x-rays and gamma rays from planetary-type objects require the instrument to be on a spacecraft at, or very close to, the object. The general form of the spectral distribution for both the planetary and celestial fluxes follows an inverse exponential relationship with energy. The sensitivity of such experiments is a prime consideration. Since the fluxes are low, the inclusion of structural or other materials which contain radioactive nuclides in the spacecraft is an interference, which, if excessive, will degrade the sensitivity of the experiment. In describing the situations which have been encountered in the integration of two such experiments on a complex spacecraft, we have in mind the relevance to future experiments of this type which will be carried on manned and unmanned missions.

Apollo 15 and 16 will carry a set of remote sensing experiments in a part of one sector of the Service Module (SM) which has been designated the Science Instrument Module (SIM) (Fig. 1). These will make observations of the Moon from orbit. Three of these instruments will be spectrometers to measure fluxes of x-rays, gamma rays, and alpha particles from the lunar surface which will provide data on the abundance of certain key elements with a spatial resolution of roughly 100 km for the Gamma Ray Spectrometer and a fourth of that for the X-Ray Spectrometer. There are no significant sources interfering with the Alpha Particle Spectrometer, so we have concentrated on the X-Ray and Gamma Ray Spectrometers for this report.

The X-Ray Spectrometer consists of three collimated proportional counters pointed at the lunar surface for the measurement of secondary x-rays produced by the interaction of solar x-rays with the upper millimeter of lunar surface material. A fourth proportional counter located on the opposite side of the SM will monitor the solar x-ray flux directly to normalize the intensity of response. The counters are all sealed, thin-window detectors capable of responding to x-rays down to 0.5 KeV. The electronic system provides eight channels of

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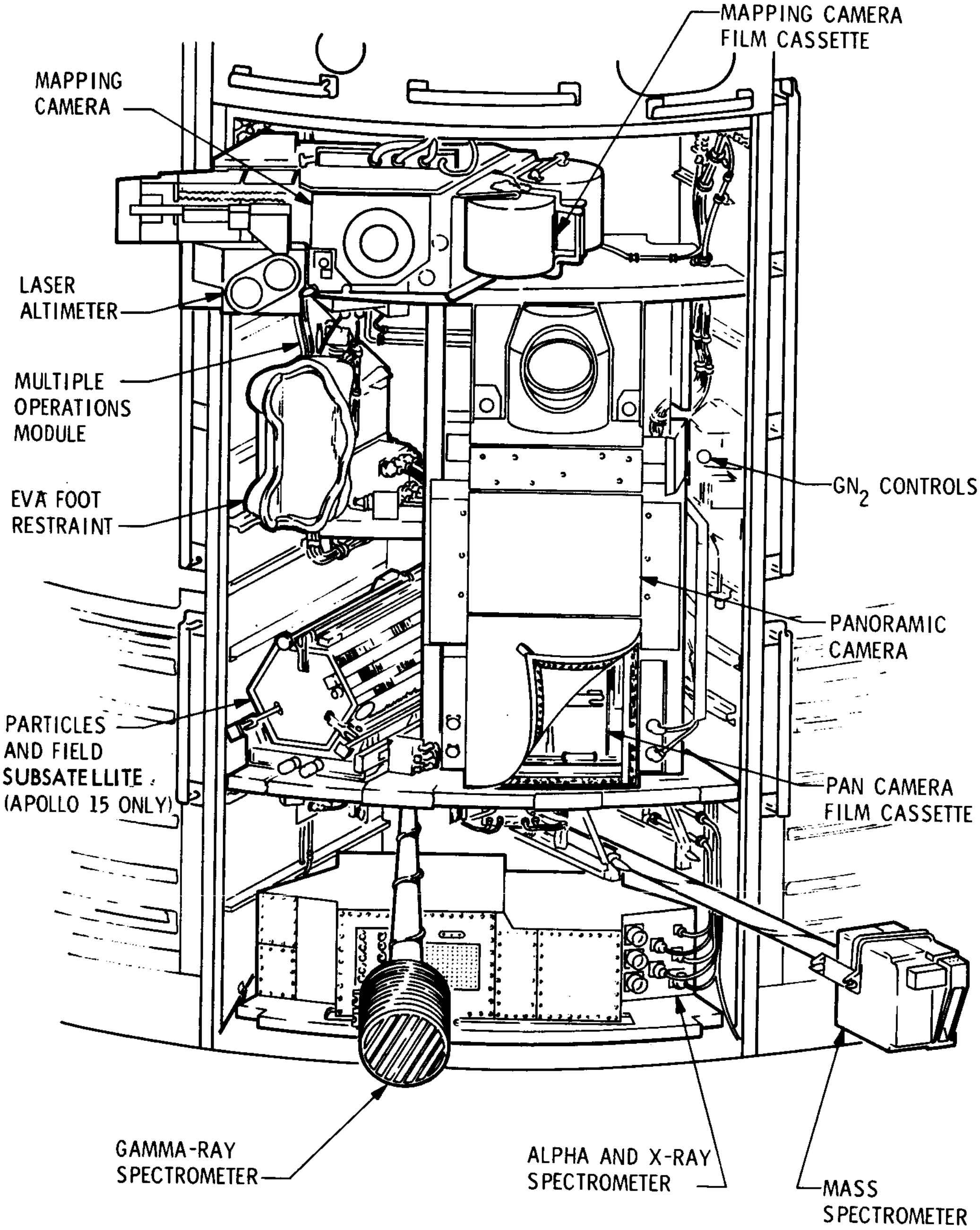

Figure 1. Location of Experiments in the SIM of Apollo 15 and 16

energy discrimination; in addition two of the lunar-directed counters will have filters to improve the resolution for characteristic x-rays of silicon, aluminum and magnesium.

The Gamma Ray Spectrometer uses a sodium iodide (NaI(Tl)) scintillator-photomultiplier tube combination as the detector. After signal amplification, a height-to-time converter and following digital electronics provide 511 channels of energy analysis which will span a nominal energy range of 0.2-9 MeV. A mantle of plastic scintillator eliminates charged particle events by detecting them in coincidence with the NaI(Tl) crystal. The detector and electronics are enclosed in a cylindrical thermal shield. The entire instrument is mounted at the end of a boom (Fig. 1) whose full extension is 25 feet. This is because gamma rays are produced by the interaction of cosmic rays with the spacecraft mass and this background interference would dominate the spectrum if the instrument were confined to the SIM even in the absence of significant quantities of natural radioactivities on the spacecraft. As it happens, significant quantities of natural radioactivities are present on the Apollo spacecraft and the boom will be essential in reducing this source of background as well as the induced component to tolerable levels.

With the Gamma Ray Spectrometer in the boom extended position, the major background component will be the induced lunar continuum with the diffuse celestial gamma ray flux making a smaller contribution. The instrumental response due to the lunar continuum has been estimated from a high altitude balloon flight experiment conducted by L. E. Peterson (Fig. 2 of Ref. 1) and the gamma ray experiment on the USSR's Luna 10 (Ref. 2), while the diffuse celestial gamma ray flux was measured initially by a Gamma Ray Spectrometer on Rangers 3 and 5 (Ref. 3); the energy region from 0.25-6 MeV was measured recently by the earth satellite, ERS-18 (Ref. 4). At energies of 1.47 MeV and 2.62 MeV which correspond to the important principal lines of K-40 and Th-232, the rates will be about 5×10^{-2} c/cm^{2}sec and 2×10^{-2} c/cm^{2}sec respectively over an energy range corresponding to the full resolution width of the gamma ray line. The three sigma statistical uncertainty has been taken as the limit of radioactive source contribution which could be tolerated without degrading experimental sensitivity. For 3000 seconds of data accumulation which corresponds to about 10 traversals over a lunar mare feature 500 km in diameter, the allowable levels are 1.6×10^{-3} c/cm^{2}sec and 1.0×10^{-3} c/cm^{2}sec for the 1.47 MeV and 2.62 MeV lines respectively. For ten hours of counting for which the spatial resolution would scale to contrast highland with mare areas, the corresponding numbers are 4.6×10^{-4} c/cm^{2}sec and 3.2×10^{-4} c/cm^{2}sec.

Sources of background interference to the X-Ray Spectrometer are again cosmic ray-induced radiation from the spacecraft and a backscattered lunar continuum. Cosmic ray-induced activity is minimized using electronic rejection methods. Coherent backscattered radiation from our calculations should be 1/10 that of the fluorescent component. Therefore we find that these sources of interferences do not significantly interfere with the measurement.

Minimum detectable source levels for the x-ray experiment cannot be compared with those of the gamma ray experiment. The minimum detectable x-ray activity is a function of the source strength of the induced activity rather than problems in the background. Because x-rays in the 1-6 KeV range of interest are much more easily absorbed than the more energetic gamma rays, the X-Ray Spectrometer can be operated in the SIM.

Detectable levels of gamma rays are low enough to require some care in the construction of the Gamma Ray Spectrometer itself since the closer to the detector the more effect a given radiation source will have. The photomultiplier tubes, crystal assembly, and thermal paint have been tested in a low background level counting facility. The smaller of the two tubes used in the instrument was found to produce a count rate at 1.47 MeV of 3.2 c/min equivalent to about 3×10^{-3} c/cm^{2}sec at the NaI(Tl) crystal, due to the presence of photoceramic spacers high in potassium. Low potassium ceramic spacers were substituted. The crystal assembly showed a small potassium response, about 2×10^{-4} c/cm^{2}sec, which was traced to the cover glass. A qualified substitute material was not available at the time so this low level of contamination was allowed to remain. The thermal paints used on the instrument are Cat-a-Lac White and Cat-a-Lac Black. Both are relatively low in potassium. Sample analyses of the two gave 0.24% by weight of potassium in the Cat-a-Lac Black, 0.008% in the Cat-a-Lac White. A calculation of the counting rate at the detector due to the paint yields 3×10^{-4} c/cm^{2}sec, below, but not greatly below the 10 hr tolerance level. However, a low level facility test of an entire detector which contains 8% of the Cat-a-Lac Black by weight but about 50% of the contribution by geometry showed no indication of potassium contamination. Aluminum rather than magnesium has been used for the instrument as a whole since some alloys of magnesium contain substantial quantities of thorium.

Radiation Sources on the Apollo J Spacecraft

The problem of radiation cleanliness was discovered early in the development of the Apollo program by examining a radiation source list maintained by the Manned Spacecraft Center. It was found that hundreds of millicuries of cobalt-60 were used to measure the reaction control system (RCS) fuel content. After extensive study and debate, this serious interference was removed. Since the time that the spectrometer experiments were chosen to fly on two of the J-series missions, increasing attention has been given to radiation cleanliness. Because of the complexity of the Apollo system and its advanced state of design when the experiments were chosen for flight, the problems have been rather severe, particularly for the Gamma Ray Spectrometer. Nevertheless, significant steps have been taken to provide the necessary environment. A strong source of thorium-232 in the base plate of the guidance system in the Command Module (CM), and ten curies of promethium-147 located on the CM were removed.

The known radiation sources aboard the Apollo spacecraft at present, their activities and locations, are listed in Table 1. Much of this data has been compiled by L. Barbieri of North American Rockwell (Ref. 5). Besides reviewing material lists, experimental radiation surveys have been conducted. Two types of surveys have been carried out, integral counting surveys with both ionization chambers and scintillation detectors, as well as surveys to determine the differential energy spectra. The integral count rate survey helped to determine major sources of radiation contamination while the differential energy spectral survey determined the nature of the contaminating isotope.

Table 1. Known Radiation Sources on Apollo 15 and 16

Radioisotope	Activity	Identification and Location
	Sources Always Present	
Potassium - 40	0.7 microcuries	EPS and ECS Radiators Thermal Paint
Potassium - 40	1.5 microcuries	KOH Electrolyte-Pyro and Re-Entry Batteries
Potassium - 40	16 microcuries	KOH Electrolyte-Fuel Cells
Potassium - 40	2.1 microcuries	LM-type Battery in SM
Potassium - 40	0.003 microcuries	Mass Spectrometer Thermal Paint
Thorium - 232	5.8 microcuries	Mapping Camera Lens
Thorium - 232	microcurie range	Guidance System Heat Sinks in CM
Mercury - 203	0.1 microcuries	Gamma Ray Spectrometer
Iron - 55	1.0 microcurie	X-Ray Spectrometer
Polonium - 210	5.0 microcuries	Alpha Particle Spectrometer
	Source Jettisoned Shortly After Lift-Off	
Uranium - 238	0.1 curie	Launch Escape System Ballast Plates
	Source Jettisoned in Lunar Orbit	
Polonium - 208	1.0 microcurie	Subsatellite Particle Detector (Apollo 15 only)
	Sources on LM Descent Stage	
Plutonium - 238	$40(10)^3$ curies	Radioisotope Thermoelectric Generator on LM
Promethium - 147	200 millicuries	Landing Point Designator Paint-LM
Potassium - 40	9.2 microcuries	Five Batteries
	Sources on LM Ascent Stage	
Tritium	14.7 curies	Portable Life Support System
Promethium - 147	21.3 curies	Radioluminescent Discs in Lunar Module
Promethium - 147	0.2 curies	Self-Luminous Switch Tips in LM
Potassium - 40	3.7 microcuries	Two Batteries

Since the information concerning the elemental composition of the lunar surface resides in the discrete lines of the measured emission gamma ray spectrum, it is very important that no discrete lines in the background spectrum occur where there are significant lines in the lunar emission spectrum. Such background lines would greatly impair our ability to determine the presence of the lunar lines. The differential energy spectrum survey thus was found to be more important because it was able to establish the existence of such interference lines. We also found that it was easier to locate the source of radiation contamination by identifying the radiation sources from their characteristic line structure. Measurements of differential energy spectra require long counting times compared to an integral counting survey. Therefore a preliminary survey was made of the total Command and Service Module (CSM) and Lunar Module (LM) areas by integral counting to find obvious problem areas. Differential spectrum determinations were carried out in the regions of suspected radiation sources and detailed studies were carried out in the stowed and extended positions for the Gamma Ray Spectrometer.

Referring to Table 1, a major source is seen to be the radioluminescent discs in the LM, amounting to 21.5 curies of promethium-147. These are used to provide orientation markers during docking maneuvers. Their location is shown in Figs. 2 and 3, together with those no longer on the CM. An early mission profile called for discard of the LM after the ascent rendevous and before operation of the lunar orbit experiments. When this was revised to retain the LM after rendevous through most of the trans-Earth phase, the radiation characteristics of the Pm-147 source were investigated. Ideally, Pm-147 has only a significant low energy bremsstrahlung spectrum, but because of the high activities involved, trace contaminants contribute significantly to the background in the spectral region of interest. Figure 4 shows a pulse height spectrum of a 300 millicurie Pm-147 source measured with a 3 in. x 3 in. NaI(Tl) detector. The source is 6 in. above the crystal. The radioisotopes producing the line spectrum have not been identified but their energies can interfere significantly with the lunar gamma ray measurement. Specifically, the 1.45 MeV line in Fig. 4 falls right on top of the 1.46 MeV line of K-40. By applying geometric and source strength factors the interference of the Pm-147 on the LM can be estimated. Twenty-one and a half curies of Pm-147 would raise the minimal detectable limit of potassium from the lunar surface by about a factor of two. Besides the interference at 1.46 MeV, the presence of the LM would alter the radiation source configuration during orbital data accumulation (since it is now planned to operate the orbital experiments both before and after ascent rendevous), and decrease the effective operating time of the Gamma Ray Spectrometer by substantially increasing its dead time. Pm-147 would also increase the background level seen by the X-Ray Spectrometer. It is therefore gratifying to report that the most recent mission profile reverts back to the original plan to discard the LM shortly after rendevous.

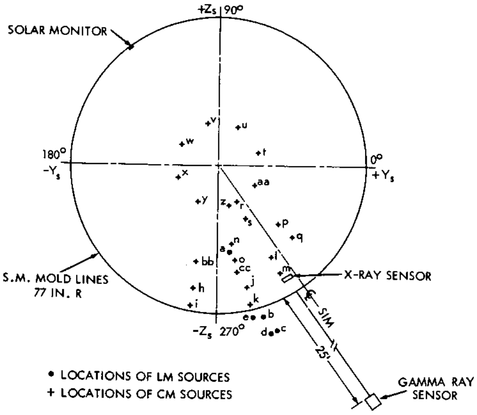

Figure 2. Location of Radioluminescent Discs

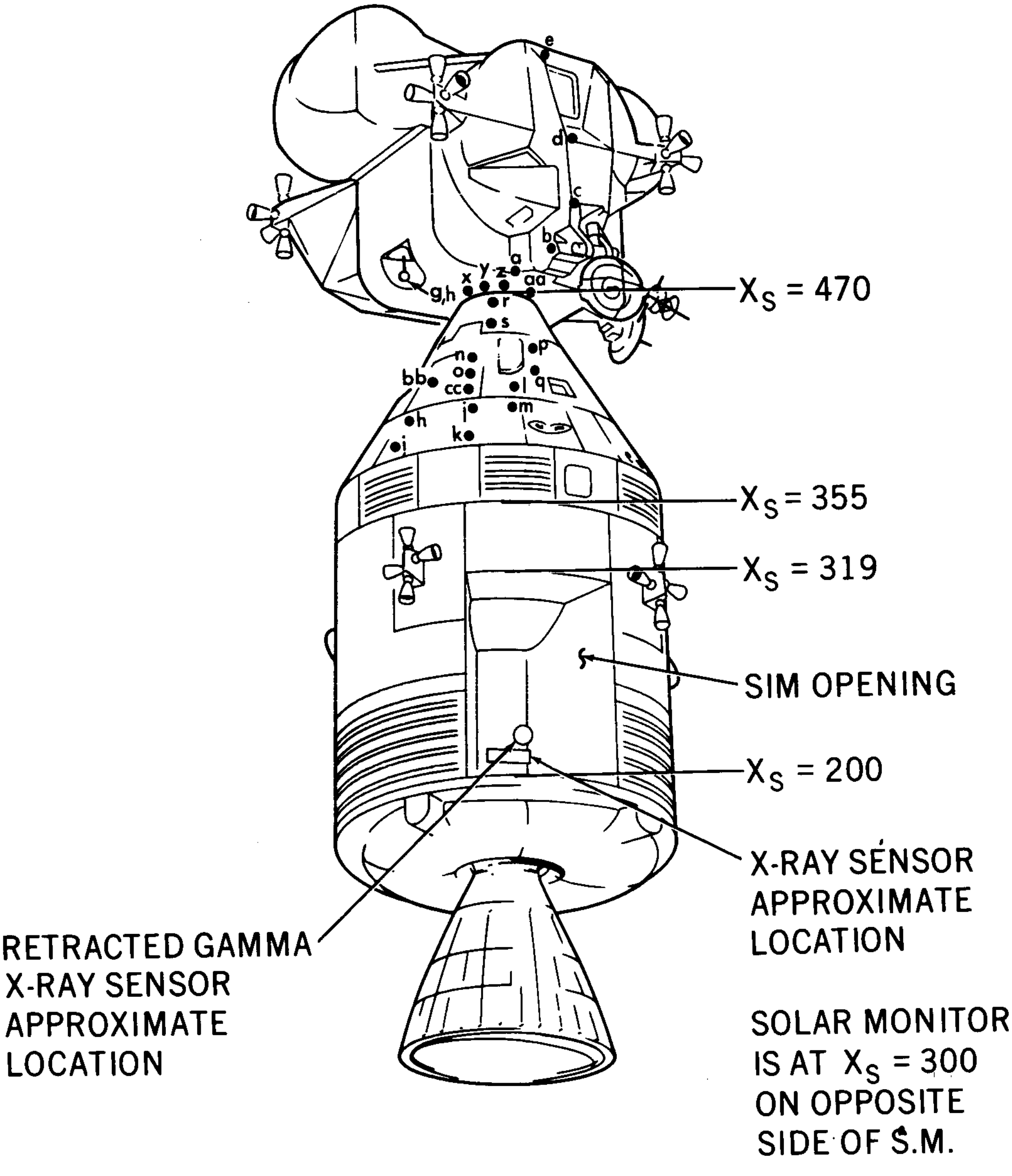

Figure 3. Relative Positions of Radioluminescent Discs and Instruments

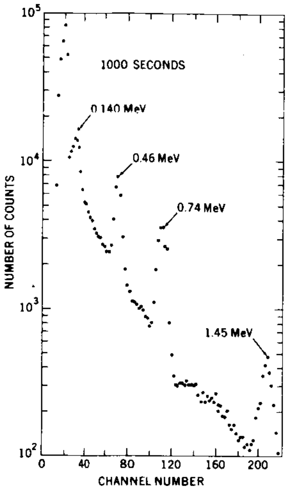

Figure 4. Pulse Height Spectrum of a 300 mc Pm-147 Source

When measurements around the SIM on the SM were carried out, the background appeared normal until added spectral lines were noticed near the top of the sector close to the CM. A spectrum taken on the middle plane level of the SIM is shown in Fig. 5. The K-40 line seen in this figure is the normal background. When the measurement was taken at the top of the SIM near the CM, characteristic lines of thorium were observed. These are shown in Fig. 6. It was later discovered that thoriated-magnesium solder was used in the CM and the thorium seen in the top of the sector is attributed to this source. Note that the difference in position of the K-40 line at 1.46 MeV seen in Figs. 5 and 6 is due to a change in gain between measurements.

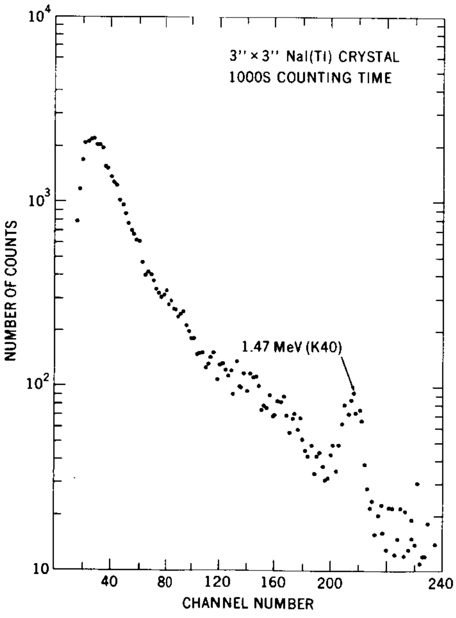

Figure 5. Pulse Height Spectrum at the Mid-Plane of the SIM

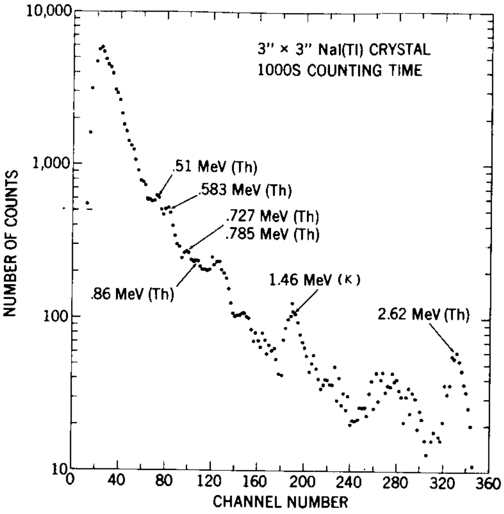

Figure 6. Pulse Height Spectrum at the Top of the SIM

The next source of radiation interference observed in the survey was that due to the potassium in the three fuel cells. The spectrum obtained near the fuel cells is shown in Fig. 7 and has a magnitude of K-40 of about four times the normal background. The general configuration of the service module (SM) is shown in Fig. 8. Since the fuel cells are stowed in sector IV on the opposite side of the SM from the Gamma Ray Spectrometer in sector I, the spacecraft itself provides shielding from this source. In order to determine the magnitude of this shielding, a Co-60 source (E_γ = 1.17, 1.33 MeV) was used to simulate the K-40 source (E_γ = 1.46 MeV); the removal cross-section does not change greatly over this energy range. Measurements were made with the cobalt source in the position of the fuel cells stowed in the SM and the scintillation detector was placed in the stowed position of the gamma ray detector. The SM was in a large bay when the measurement was made. There was an empty bay with no SM present and the geometric configuration of source and detector was simulated in the empty bay. The comparison of the two spectra, i.e., with the spacecraft present and in the empty bay is shown in Fig. 9. From this figure one sees that the flux is decreased by an order of magnitude at the peak energy due to the shielding effect of the spacecraft.

The three fuel cells, each of which contains 10 kg of KOH electrolyte, are the dominant radiation source of K-40 (16μc) but there are several others. Not counting the batteries in the LM which will not affect the experiments, there are three re-entry and two pyro-batteries in the lower equipment bay of the CM as well as a larger LM-type battery in sector IV of the SM. These batteries together contain 3.6μc of K-40. Next, the Z-93 thermal control paint used on the environmental control system and electric power system thermal radiators which are widely distributed

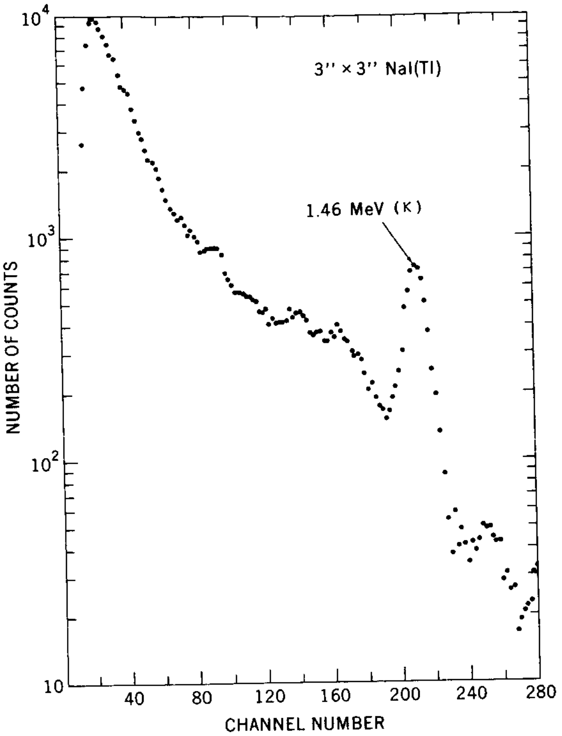

Figure 7. Pulse Height Spectrum near the SM Fuel Cells

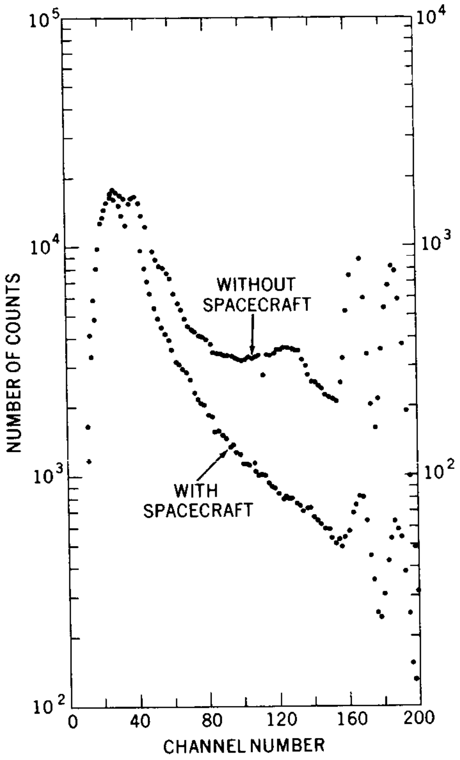

Figure 9. Spacecraft Shielding of the Fuel Cell Radiation Source

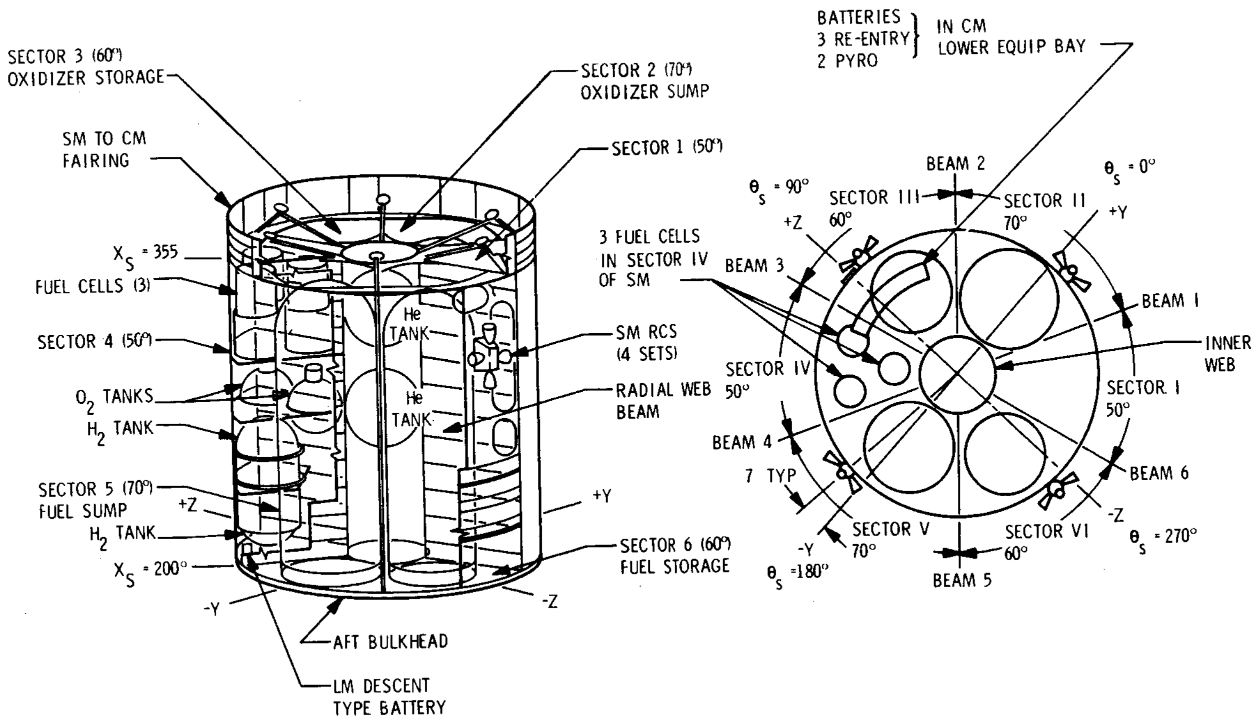

Figure 8. Apollo SM General Configuration

around the SM, contains a high percentage of potassium with a total activity calculated at 0.7μc of K-40. Summing the quantities of potassium in the fuel cells, batteries and thermal paint, the flux will exceed the 10 hr 3 sigma tolerance level at the boom extended position by a factor of 2-3 when spacecraft shielding is not considered; shielding will reduce it below the tolerance level.

One other source of potassium is worth mentioning. It was discovered relatively recently that the mass spectrometer will use a thermal control paint (MS-74) containing about 25% potassium. The Mass Spectrometer also extends out from the SIM on a boom (Fig. 1) but at a distance from the Gamma Ray Spectrometer which makes the contribution of this source negligible.

A non-negligible source is the 53 gm thorium contained in the lens of the Mapping Camera for the purpose of providing the proper index of refraction. A special survey of one such lens was made and a typical spectrum is shown in Fig. 10. This source has spectral lines which are identical to those of interest from the lunar surface. The expected flux is several times the 3 sigma tolerance value, depending in part on the degree of radioactive equilibrium reached by the daughter products. No natural spacecraft shielding is available in this case; the lens looks directly at the Gamma Ray Spectrometer when the latter is deployed. Accordingly, a tungsten shield will be provided to reduce the radiation level from the lens. This shield will cover the lens during most of the time that gamma ray spectra are being obtained.

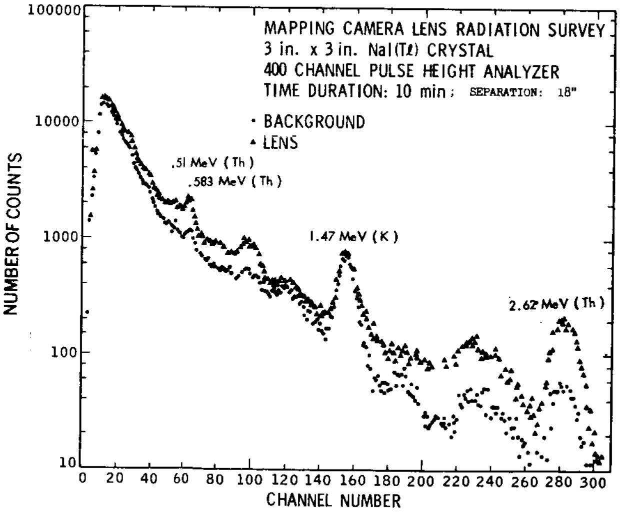

Figure 10. Pulse Height Spectrum of the Mapping Camera Lens

It remains to consider the strongest source of all on Apollo, the SNAP-27 radioisotopic thermoelectric generator which is fueled by 40,000 curies of Pu-238 and powers the ALSEP package on the lunar surface. The orbital experiment phase will not begin until after the LM has descended to the lunar surface, but because of a recent change in the event-time sequence, thermal considerations require that the instrument be powered sometime before separation of the LM. This gave rise to concern that the resultant count rate of the Gamma Ray Spectrometer might be high enough to damage the instrument. Flux measurements of Apollo 14's SNAP-fuel element have been applied to the SNAP-Gamma Ray Spectrometer spacecraft geometry to yield a maximum expected rate of 2 Kc, well within the limit of safety. Analogous data on the fuel elements for Apollo 15 and 16 will be obtained before launch for confirmation.

The remaining sources listed in Table 1 are either low in energy or intensity and pose no problem for either spectrometer.

Conclusions

The following observations may be made:

1. Distance is extremely effective in reducing source interference. Use of the inverse square relationship plus shielding allows radiation-sensitive experiments to be performed on the same spacecraft with relatively strong sources. This procedure will prove most effective for the Gamma Ray Spectrometer.
2. Early knowledge of the sources present and their characteristics can minimize the problems of radiation interference by pointing the way to early solutions; e.g., removal, alternate location or shielding.
3. A radiation source specification which defines tolerable limits of both line and continuum radiation and also lists materials to be avoided can reduce the quantity of radiation source materials used on a spacecraft. Such a specification is easier to prepare than to implement however.
4. Radiation surveys are useful in identifying sources and their characteristics. A survey of the entire CSM for Apollo 15 is scheduled.*
5. The mission profile has had a major effect on the radiation source situation in two respects; i.e., disposition of the LM and time of instrument turn-on. When such options exist and if they can be anticipated sufficiently far in advance, they should be considered in the design of the instrument and in the determination of the spacecraft-instrument configuration.

The authors are pleased to acknowledge the extensive contributions of Louis J. Barbieri and Gary Wengrow to these studies, the assistance of Richard L. Schmadebeck in performing some of the surveys and the many helpful discussions they have had with James R. Arnold.

* Note added in press: The radiation survey of the Apollo 15 CSM has revealed the fact that, contrary to our expectation, the thorium sources have not been removed from the base plate of the inertial guidance system. The base plate is 24"x24", and is mounted horizontally somewhat off axis in the direction away from the SIM. Set into the plate are a number of heat sinks made of thoriated magnesium, the combined intensity of which is presently estimated to be in the range of 30 microcuries. This is undoubtedly the source of the thorium lines seen in Figure 6. A solution to this problem is being sought.

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