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APOLLO EXPERIENCE REPORT - PROTECTION AGAINST RADIATION

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16. Abstract Radiation protection problems on earth and in space are discussed. Flight through the Van Allen belts and into space beyond the geomagnetic shielding was recognized as hazardous before the advent of manned space flight. Specialized dosimetry systems were developed for use on the Apollo spacecraft, and systems for solar-particle-event warning and dose projection were devised. Radiation sources of manmade origin on board the Apollo spacecraft present additional problems. Methods applied to evaluate and control or avoid the various Apollo radiation hazards are discussed.					
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APOLLO EXPERIENCE REPORT

PROTECTION AGAINST RADIATION

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SUMMARY

Radiation was not an operational problem during the Apollo Program. Doses received by the crewmen of Apollo missions 7 to 15 were small because no major solar-particle events occurred during those missions. One small event was detected by a radiation sensor outside the Apollo 12 spacecraft, but no increase in radiation dose to the crewmen inside the spacecraft was detected. Solar-particle releases are random events, and it is possible that a flare, with the accompanying energetic nuclear particles, may hinder future flights beyond the magnetosphere.

Radiation protection for the Apollo Program was focused on both the peculiarities of the natural space radiation environment and the increased prevalence of manmade radiation sources on the ground and on board the spacecraft. Radiation-exposure risks to crewmen were assessed and balanced against mission gain to determine mission constraints. Operational radiation evaluation required specially designed radiation-detection systems on board the spacecraft in addition to the use of satellite data, solar observatory support, and other liaison.

Control and management of radioactive sources and radiation-generating equipment have been important in minimizing radiation exposure of ground-support personnel, researchers, and the Apollo flight and backup crewmen. Problems of radiation protection that influence space flights as well as ground operations are discussed and the solutions documented.

INTRODUCTION

The Apollo experience in radiation protection includes two distinct areas: space, where the largest and most critical radiation sources are virtually uncontrollable, and earth, where most radiation sources of appreciable strength are manmade and controllable. The basic philosophy of radiation protection in these two areas remains the

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same; that is, to avoid harmful effects of radiation by limiting the radiation dose to the lowest level judged consistent with the achievement of beneficial goals.

PROBLEMS RELATING TO THE SPACE RADIATION ENVIRONMENT

Although the Apollo missions have placed men outside the protective geomagnetic shielding and have subjected them to types of ionizing radiation seldom encountered in earth environment, radiation doses to Apollo crewmen have been minimal (table I). Spacecraft transfer from low earth orbit to translunar coast necessitates traverse of the regions of geomagnetically trapped electrons and protons known as the Van Allen belts. When beyond these belts, the spacecraft and crewmen are continuously subjected to high-energy cosmic rays (ref. 1) and to varying probabilities of particle bursts from the sun (fig. 1).



Figure 1. - Radiation-dose estimates for particle events between June 1968 and December 1969.

In table I, the tabulated radiation doses are the averages of all readings on the thermoluminescent dosimeters for the respective mission. Individual dosimeter readings have varied approximately 20 percent from the average because of variations in the shielding effectiveness of the Apollo spacecraft and the differences in duties, movements, and locations of the crewmen. Doses to blood-forming organs are approximately 40 percent lower than the values measured at the body surface. In comparison with the doses actually received, the maximum operational dose (MOD) limit for each of the Apollo missions was set at 400 rads (X-ray equivalent) to skin and 50 rads to the blood-forming organs.

TABLE I. - AVERAGE RADIATION DOSES OF
THE FLIGHT CREWS FOR THE
APOLLO MISSIONS

Apollo mission	Skin dose, rads
7	0.16
8	.16
9	.20
10	.48
11	.18
12	.58
13	.24
14	1.14
15	.30

Van Allen Belts

The problem of protection against the natural radiations of the Van Allen belts was recognized before the advent of manned space flight. The simplified solution is to remain under the belts (below an altitude of approximately 300 nautical miles) when in earth orbit and to traverse the belts rapidly on the way to outer space. In reality, the problem is somewhat more complex. The radiation belts vary in altitude over various parts of the earth and are absent over the north and south magnetic poles. A particularly significant portion of the Van Allen belts is a region known as the South Atlantic anomaly (fig. 2). Over the South Atlantic region, the geomagnetic field draws particles closer to the earth than in other regions of the globe. The orbit inclination of a spacecraft determines the number of passes made per day through this region and, thus, determines the radiation dose that will accompany these passes for a set altitude and spacecraft shielding.

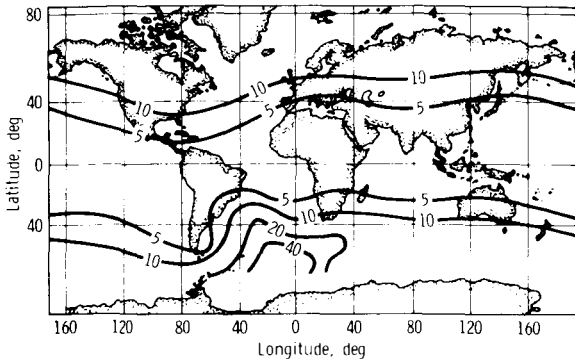


Figure 2. - Isodose profile showing high-dose region over the South Atlantic (values are in mrad/day at an altitude of 210 km).

A major complication concerning radiation stability within the belts (including the South Atlantic anomaly portion) is a result of high-altitude nuclear detonations. In 1962, the United States detonated a 1.5-megaton thermonuclear device (Project Starfish) in a portion of the Van Allen belt region and caused the radiation levels within the belts to rise significantly. By 1969, the high-energy electron component of the injected radiation had decayed to only one-twelfth of the 1962 intensity. The small amount of time spent in earth orbit and the rapid traverse of the radiation belts during Apollo missions have minimized astronaut radiation dose from the remaining Starfish electrons. However, recurrence of high-altitude nuclear testing would

have a significant impact on Apollo earth-orbit operations, and this possibility has been factored into radiation-protection planning for Apollo space missions. Sources of current intelligence information on nuclear-device testing are available to the NASA, and these sources are ready to assist in the real-time management of any contingency that might be caused by the high-altitude detonation of a nuclear device.

Particles within the Van Allen belts spiral around the earth magnetic lines of force and, therefore, display directionality. This directionality varies continuously in angular relationship to the trajectory of the spacecraft. Therefore, dosimetry instrumentation in the Van Allen belts must use relatively omnidirectional radiation sensors so that the radiation flux will be measured accurately. The Van Allen belt dosimeter (VABD) (fig. 3) was designed specifically for Apollo dosimetry within these radiation belts and has proved satisfactory because dose values derived from its greater than 180° radiation acceptance angle have correlated well with doses indicated by postflight analyses of passive dosimeters worn by the crewmen. The nuclear-particle-detection system (NPDS) (fig. 4) was designed to have a relatively narrow acceptance angle and was intended to measure the isotropic proton and alpha particles derived from solar-particle events. Experience with the NPDS within the highly directional radiation fields of the Van Allen belts has emphasized the difficulty in determining true flux levels using a detector of narrow angle response. There are two problems in determining flux levels. First, orientation of the spacecraft relative to the direction of the impinging particles is not precisely known at all times. Second, even if orientation were precisely known, inaccuracy would result from the high statistical error inherent with low counting rates when the detector is pointed away from the direction of particle flux.

A compromise in VABD design was required for Apollo flammability considerations, and this compromise resulted in the use of aluminum as a replacement for tissue-equivalent plastic in the ionization-chamber walls. Aluminum is a satisfactory replacement for tissue-equivalent plastic only if electron secondary radiation (bremsstrahlung) is a small portion of the total radiation dose (as in the Apollo Program). Chambers of tetrafluoroethylene plastic would be preferable to aluminum if flammability remains a design factor for future missions. A detailed discussion of radiation dosimetry considerations for post-Apollo missions is contained in references 2 and 3.

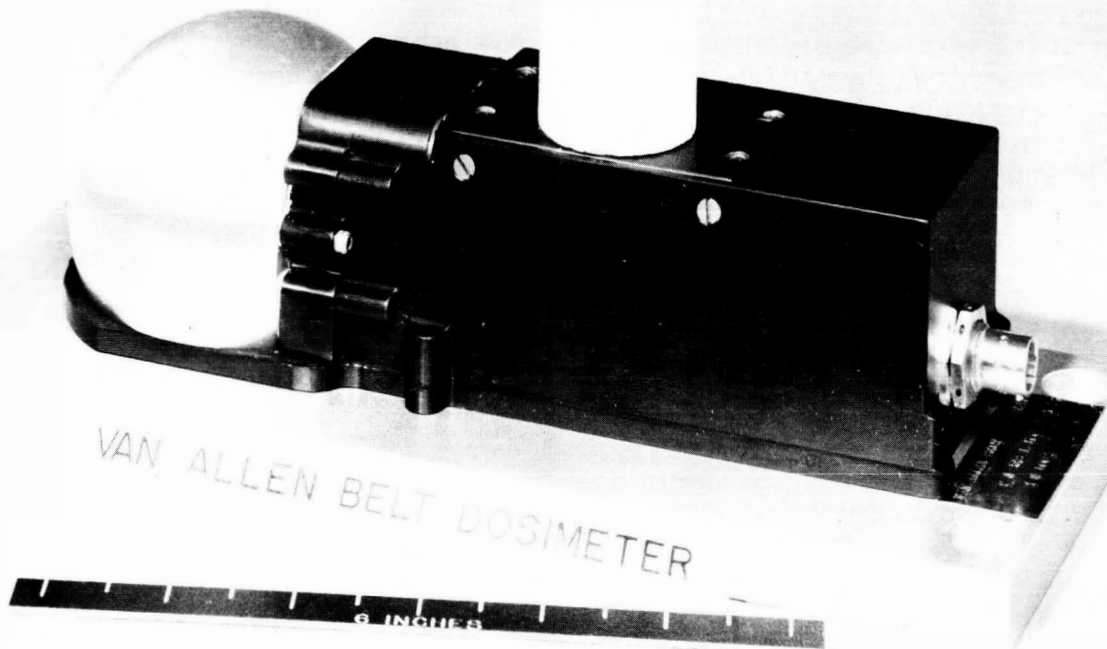


Figure 3. - Van Allen belt dosimeter.

Solar-Particle Events

No major solar-particle events have occurred during an Apollo mission (fig. 1). Although much effort has been expended in the field of solar-event forecasting, individual eruptions from the solar surface are impossible to forecast. The best that can be provided at this time is an estimate of particle dose, given visual or radio-frequency (RF) confirmation that an eruption has occurred. A system of solar-monitoring stations, the Solar Particle Alert Network (SPAN), provides a NASA-sponsored network of continuous data on solar-flare activity. The various components of this network are described in the appendix. Approximately 20 percent of the largest solar flares (importance 2 bright or larger) will result in particle fluxes in the earth/moon region that can be related in intensity to early RF or visual characteristics. A warning interval of from less than one to several hours (typically, 2 to

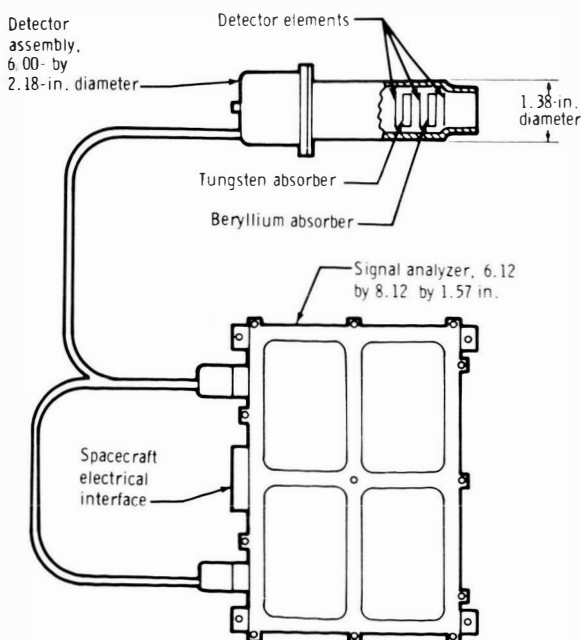


Figure 4. - Nuclear-particle-detection system.

4 hours) is obtained between the RF/visual indication and the appearance of particles in the earth/moon region. Because only approximately 20 percent of the flares result in particle events, it is not necessary to change normal mission procedures on the basis of RF or visual observations alone. Rather, radiation sensors on board solar-orbit and earth-orbit satellites, as well as on board the Apollo spacecraft itself, are used to confirm the particle event. Only after the appearance of particles is confirmed would action be taken to protect the crewmen. For a typical event, approximately 8 hours would be available from the time particles are confirmed to the time of peak radiation dose. Details concerning effects of solar-particle events on various phases of an Apollo mission are shown in table II.

TABLE II. - SOLAR-FLARE RULES FOR APOLLO MISSIONS

Condition	Mission phase	Rule	Comments
Major solar flare has been predicted.	All	Continue mission.	
Major solar flare has occurred.			
Unconfirmed particle event has occurred.	All	Continue mission.	Report: particles have not been confirmed. No mission impact is indicated.
Confirmed particle event and SPAN or real-time analyses indicate the MOD will be exceeded during the mission.	Prelaunch	Hold until data analysis indicates that the MOD will not be exceeded.	
	Earth parking	Continue mission. If data analysis indicates that the MOD will be exceeded by a significant amount before mission completion, translunar injection is no-go.	Translunar injection is no-go only if firm computation before go/no-go indicates more than the MOD.
	All other phases	Continue mission. Consideration will be given to early (or extended) transearth injection and inhibiting crew transfer to the lunar module.	
Confirmed particle event and spacecraft telemetry or personal radiation dosimeter read-out projections indicate the MOD will be exceeded during the mission.	Translunar coast	Continue mission. Consideration should be given to entering in next best preferred target point if the total dose can be reduced significantly without increasing total risk to the crew.	Crew should begin personal dosimeter and radiation survey meter read-outs. A projection of greater than the MOD is not required for crew read-outs.
	Lunar orbit	Continue mission. Consider extending lunar orbit stay time if the total dose to the crew would be reduced significantly by lunar shielding.	Hatch-down attitude may be used to reduce the total dose. If a particle event is confirmed, the crew will transfer from the lunar module to the command and service module.
	Lunar stay	Consider reducing the lunar stay time or extravehicular activities if the total dose to the crew can be reduced significantly without increasing the total risk to the crew.	Comparison of command and service module and lunar surface personal radiation dosimeters is advised.
	All other phases	Continue mission.	

In terms of hazard to crewmen in the heavy, well-shielded command module, even the largest solar-particle event on record (November 12, 1960) would not have caused any impairment of crewmember functions or ability of the crewmen to complete their mission safely. It is estimated that within the command module during this event the crewmen would have received a dose of 60 to 100 rads to their skin and 10 to 30 rads to their blood-forming organs (bone and spleen) (refs. 4 and 5). Other estimates have indicated that skin dose from this event could have been as high as 270 rads. Radiation doses to crewmen while inside the thinly shielded lunar module or during an extravehicular activity (EVA) would be significantly higher for such a particle event. The radiation specialists at the Mission Control Center Space Environment Console, with the assistance of SPAN and the other monitoring system described in the appendix, must advise the Flight Director and Flight Surgeon of the radiation risks that would be involved with the event. If doses are projected to be detrimentally high, it would be advised that the astronauts not stay in the lunar module or perform EVA during this type of particle event. Rules that apply to lunar module stay or EVA during such an event are indicated in table II under the mission phases "Lunar orbit" and "Lunar stay."

Cosmic Rays

Cosmic-ray fluxes have provided average dose rates of 1.0 mr/hr in cislunar space and 0.6 mr/hr on the lunar surface. These values are expected to double at the low point in the 11-year cycle of solar-flare activity (solar minimum) because of decreased solar magnetic shielding of the central planets. The effect of high-energy (but low dose rate) cosmic rays on humans is unknown but is considered by most authorities to be of relatively minor consequence for exposures of less than a few years. Experimental evidence of the effects of these radiations is dependent on the development of highly advanced particle accelerators or the advent of long-term manned missions outside the geomagnetic influence.

One particular effect possibly resulting from cosmic rays has been the light-flash phenomenon reported on the Apollo 11 and subsequent missions. Although ionizing radiations can produce visual phosphenes (subjective sensations best described as flashes of light) of the types reported, a definite correlation has not been established between cosmic rays and the observation of flashes. The light flashes have been described as starlike flashes or streaks of light that apparently occur within the eye. The flashes are observed only when the spacecraft cabin is dark or when blindfolds are provided and the crewmen are concentrating on detection of the flashes. There is a possibility that visual flashes may indicate the occurrence of damage to the brain or eye; however, no damage has been observed among crewmen who have experienced the light-flash phenomenon.

Additional investigations during future Apollo missions are planned to provide a better understanding of the cause of the visual light flashes and any possible detrimental consequences. These investigations will include careful observations and reporting procedures to define the frequencies and characteristics of the visual events. Correlation of visual events with cosmic-ray flux rates will be determined by real-time recording of cosmic-ray interactions near the crewmen's heads during periods of light-flash observation.

Neutrons

Neutrons created by cosmic rays in collision with lunar materials were postulated to be a potential hazard to Apollo crewmen (ref. 6). It has been proposed that the neutron hazard be evaluated by the use of whole-body activation measurement of crewmen to determine the extent of neutron-induced sodium-24 and by use of neutron-resonant metal foils that have a known activation response for the type of neutrons expected. Both methods for neutron-dose assessment have been used at the NASA Manned Spacecraft Center (MSC). Whole-body counting and neutron-resonant foil techniques had been initiated on the Apollo 11 mission. The results of these analyses indicated that neutron doses were significantly lower than had been anticipated. Activation products were below the limits of detection by whole-body spectroscopy, and activities were extremely low even in the neutron-resonant foils (ref. 7). The whole-body and neutron-resonant foil methods of neutron-dose determination have been retained because of the remaining potential for neutron production by solar-event particles or for excessive crewman exposure to neutrons from the SNAP-27 radioisotope thermal generator used to power the Apollo lunar surface experiments packages.

OVERALL RADIATION SPECTRUM

During a complete Apollo mission, astronauts are exposed to widely varying fractions of radiations from the Van Allen belts, cosmic rays, neutrons, and other subatomic particles created in high-energy collisions of primary particles with spacecraft materials. In addition, the individual responsibilities of the crewmen differ, and, therefore, radiation exposure may differ.

To allow accurate determination of radiation exposure of the crewman, each carries a personal radiation dosimeter (PRD) (fig. 5) and three passive dosimeters (fig. 6). The PRD provides visual read-out of accumulated radiation dose to each crewman as the mission progresses. The PRD is approximately the size of a cigarette pack, and pockets are provided in the flight coveralls, as well as in the space-suit, for carrying the PRD. The passive dosimeters are placed in the garments that are worn throughout the mission. The passive dosimeters contain lithium fluoride thermoluminescent dosimetry powder, nuclear emulsions, neutron-dosimetry foils, and foils for detection of high-atomic-weight cosmic particles. These detector materials are analyzed after each mission, and an accurate determination of the radiation dose to various portions of the body (ankle, thigh, and chest) is facilitated. In addition, the passive dosimeter provides detailed information on the types of radiation to which each astronaut is exposed.

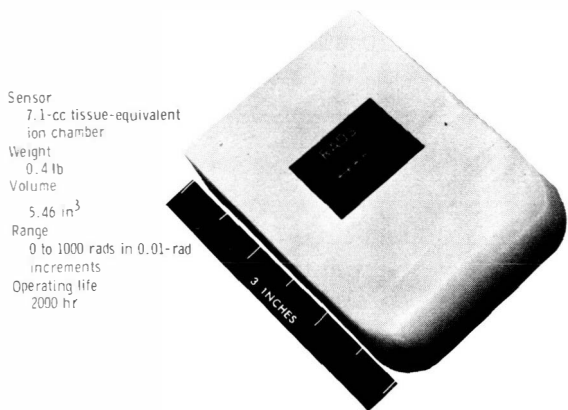


Figure 5. - Personal radiation dosimeter. (fig. 7) is taken on each Apollo mission.

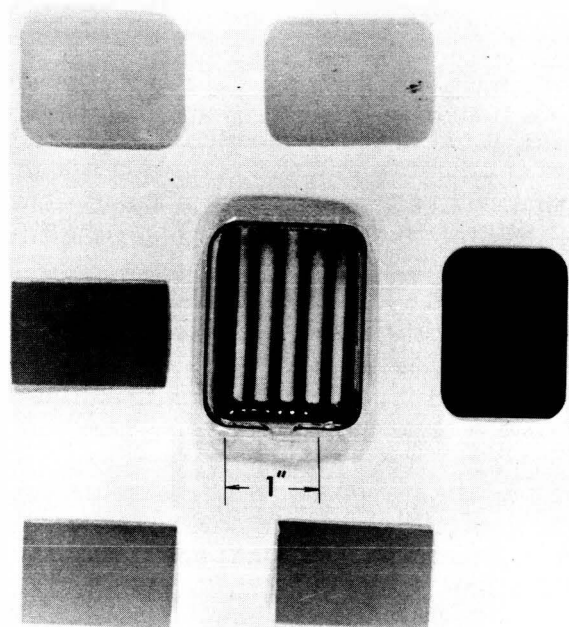


Figure 6. - Passive dosimeter with component parts.

Sensor	10-cc tissue-equivalent ion chamber	Range: linear	
Weight	1.60 lb	0 to 100	} rads/hr
Volume	23 in ³	0 to 10	
		0 to 1	
		0 to 0.1	
		Operating life	1200 hr

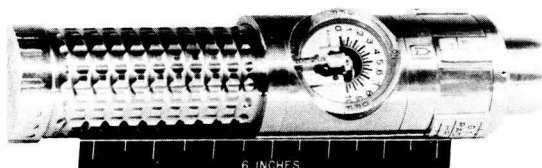


Figure 7. - Radiation-survey meter.

The RSM is a direct-reading dose-rate instrument that allows the crewmen to determine radiation levels in any desired location in their compartment. The crewmen would use the RSM to find a habitable low-dose region within the spacecraft in the event of a radiation emergency. If desired, the RSM can be stowed in its wall bracket with its meter turned on, so that continuous onboard dose-rate read-out may be obtained.

PROBLEMS INVOLVING RADIATIONS OF MANMADE ORIGIN

Protection against manmade sources of radiation is a ground-support function concerned mainly with the protection of the ground personnel, the general public, and the environment against detrimental effects of ionizing radiation. Much of this effort is routine health-physics procedure governed by U. S. Atomic Energy Commission regulations (ref. 8) and U. S. Department of Labor standards (ref. 9). However, certain problems involving spacecraft radioluminescent sources apply directly to the Apollo experience and are discussed in detail.

Radioluminescent Switch Tips

Lunar module switch tips contain microspheres of promethium-147 bound with a phosphor that produces light by interaction with the short-range promethium-147 beta radiation. Originally, many switch tips were manufactured as type 19, and acrylic plastic enclosed the microspheres. The acrylic plastic sealed in the radioactive material and also shielded out the ionizing radiations while allowing the passage of light. Later, the fire hazard from the acrylic plastic was recognized, the encapsulating material was changed to Kel-F plastic, and an epoxy plug was used to seal the radioactive microspheres in a cylindrical hole within the Kel-F. The Kel-F/epoxy tips are designated type 39.

Type 19 tips were used on board the lunar module simulators where no flammability hazard existed because the atmosphere was not oxygen enriched. Flight vehicles were equipped with type 39 tips. Both types of tips failed (leakage of more than 5×10^3 picocuries) because of radiation self-degradation of the encapsulation materials and subsequent leakage of promethium-147. No personnel injury was caused by these failures. However, cleanroom facilities were shut down for a period of 14 hours before the launch of the Apollo 10 mission when several leaking tips onboard the lunar module required last-minute replacement.

The problem of leakage was solved by encapsulating the microspheres in glass before sealing with epoxy in Kel-F. The resultant tip is designated type 59. The new type 59 tip has replaced all type 19 simulator tips and all type 39 flight-qualified tips.

Radioluminescent Panels

Promethium-147 microspheres were used in a luminescent paint applied to panels on the lunar communications relay unit and on the lunar roving vehicle. A thin coating of acrylic plastic was applied over the paint as a sealant. When the panels arrived at the MSC for testing, it was found that the acrylic coating was too thin to reduce radiation levels to limits acceptable for handling. The problem was solved by applying a layer of 1/16-inch Kel-F plastic over the panels during testing procedures. The plastic layer reduced the soft X-ray dose from an initial value of approximately 13 rads/hr at a distance of 2 inches from the panels to an acceptable value of less than 0.3 rad/hr. The panels were not considered hazardous to the crewmen during missions because the space suits provide more than the equivalent shielding of 1/16-inch Kel-F. Therefore, plastic covers were not required on flight units.

Radioluminescent Lighting

The portable life support system (PLSS) worn by the crewmen on the lunar surface has a remote control unit (RCU) that contains the controls and the quantity gages for the PLSS. The requirement for lighting the RCU was met by using small hydrogen-3-activated, glass-encapsulated, radioluminescent light sources imbedded in the polycarbonate plastic top cover of the unit. These light sources were modified commercially available units (Beta lights). No external radiation was detected in association with the Beta lights. These lights have performed satisfactorily where indirect lighting can be used. Also, the Beta lights eliminate the external radiation problems and the effect on scientific measurements that occur when the promethium-147-activated systems are used.

CONCLUDING REMARKS

Apollo missions have not undergone any major space radiation contingency. However, the development of spacecraft dosimetry systems, the use of a space radiation surveillance network, and the availability of individuals with a thorough knowledge

of the space radiation environment have assured that any contingency would be recognized immediately and would be coped with in a manner most expedient for both crew-member safety and mission objectives.

Routine radiation-protection problems dealing with manmade radiation sources have been solved by using standard health-physics procedures. Spacecraft radioluminescent-light-source problems were solved by improvement in shielding and containment of the promethium-147 isotope. It has been shown on the Apollo missions that the spacecraft and its crewmen have successfully avoided the large radiation doses that, before the Apollo missions, had been cited as a possible deterrent to manned space flight. Radiation doses to Apollo crewmen have been significantly lower than the yearly average of 5 rem set by the U. S. Atomic Energy Commission for workers who use radioactive materials in factories and institutions across the United States. More significantly, Apollo astronaut doses have been negligible in terms of any medical or biological effects that could impair the function of man in the space environment. Close coordination among mission planners, the Radiation Safety Committee, the Radiological Health Team, and the Radiation Constraints Panel ensures that radiation exposures under nominal conditions will continue to remain minimal.

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National Aeronautics and Space Administration
Houston, Texas, October 24, 1972
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APPENDIX

SOLAR-PARTICLE-MONITORING NETWORK SYSTEM

SOLAR PARTICLE ALERT NETWORK

The Solar Particle Alert Network (SPAN) consists of three multiple-frequency radio telescopes and seven optical telescopes that are operated under contract to the NASA. The SPAN provides data for determining the severity of solar-particle events and the resultant possible radiation hazards to the crewmen. Solar-event data, when used for mission support, are sent by teletype directly to the Space Environment Console (SEC) at the Manned Spacecraft Center Mission Control Center. Radiation experts at the SEC evaluate the data and concurrently increase their watch of earth-based, satellite and spacecraft radiation sensors to determine early signs of particle-flux increase in the earth/moon region.

SOLAR FORECAST CENTER

The Solar Forecast Center (SFC) is located in the North American Air Defense Command, Cheyenne Mountain Complex, Colorado Springs, Colorado, and is manned by personnel of Detachment 7, Fourth Weather Wing, Ent Air Force Base, Colorado. Detachment 7 includes a worldwide Solar Observing and Forecasting Network (SOFNET) as well as the SFC. Personnel of the Fourth Weather Wing augment the staffs of several solar observatories. These observatories are located at Sacramento Peak, New Mexico; Sagamore Hill, Massachusetts; South Point, Hawaii (SPAN site); Athens, Greece; Manila, Philippines; Teheran, Iran (SPAN site); and Los Angeles, California. The personnel at these SOFNET observatories, along with personnel at several other cooperating observatories and agencies, maintain a continuous surveillance of the sun and send real-time solar and geophysical data to the SFC. These data are received 24 hours a day at the SFC and are plotted and analyzed by the solar forecasters on duty. On the basis of analysis of these reports, the SFC issues four routine forecasts each day, an extended period forecast each week, and special-activity alerts. During Apollo mission periods, these forecasts and alerts are sent to the SEC to aid support personnel in keeping track of solar activity.

SPACE DISTURBANCE FORECAST CENTER

The Space Disturbance Forecast Center (SDFC) is a part of the Space Disturbance Laboratory, National Oceanographic and Atmospheric Administration, and is located at Boulder, Colorado. The SDFC operates one of the seven SPAN optical telescopes and serves as a collection point for data from a number of monitoring stations located near Boulder. The SDFC is operated 24 hours a day and provides support to various Government agencies in the form of solar forecast prepared and sent out every 12 hours. In

addition to the 12-hour forecasts, the SDFC will transmit other solar-activity data to the SEC during mission periods. Data will be transmitted by way of teletype through NASA Goddard Space Flight Center or by telephone directly to the SEC.

OPTICAL TELESCOPE SYSTEM

The optical telescope system is used to observe and locate the major centers of activity on the solar disk. Solar eruptions or flares occurring in these active regions can be observed for characteristics associated with particle-producing events. When a solar-flare event occurs, it is recorded by a camera that photographs the solar disk as viewed through the telescope. Observations are reported routinely to the SDFC in Boulder; and, during mission-support periods, telephone or radio reports are made directly to the SEC in Houston.

RADIO-FREQUENCY TELESCOPE SYSTEM

The RF telescope system will detect and record the intensity of solar radio emissions in the microwave region at frequencies of 1420, 2695, and 4995 megahertz. Observations are reported to the SDFC or, for optical events, to the SEC. The time-integrated radio emissions vary with the solar cycle. During periods of marked solar activity, outbursts of radio energy from two times to more than 50 times the normal background signal may occur for short periods usually lasting less than 3 hours. The simultaneous detection of an RF burst at all three frequencies indicates the reception of synchrotron emission from electrons accelerated in the solar magnetic fields. Proton acceleration and release of protons and other charged nuclear particles by the solar event are implied when the RF synchrotron emission is detected. Approximately 20 percent of such particle releases result in the appearance of particles in the earth/moon region.

RIOMETER SYSTEM

The riometer (relative ionospheric opacity meter) system is a highly sensitive, ultrastable system operated for the NASA under support agreements for measuring intensities of electromagnetic fields. The riometer measures the changes in absorption of cosmic radio noise as it traverses the ionosphere. Such changes are caused by variations in electron density within the ionosphere brought about by solar atmospheric disturbances or high-altitude nuclear events. The electron density profile is a function of the spectrum of protons incident on the atmosphere causing ionization. Therefore, by using riometers at different frequencies, estimates can be made of proton flux and spectra. When required for mission support, the system reports directly to the SEC.