RADIATION PROBLEMS ASSOCIATED WITH SKYLAB

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Skylab, an experimental space station, will orbit the earth during 1972-73. Sixty experiments will be carried out during its flight, 26 of which use some type of photographic film. In its circular orbit of 235 n mi, inclined 50°, it passes through the Van Allen belt several times a day. The expected radiation environment is too severe for some of the film on board. In addition, it was suspected that this environment would darken a borosilicate window used by the S190 experiment. Radiation tests were conducted on the various types of Skylab film to establish the total radiation dosages compatible with an acceptable level of film fogging, and on the S190 borosilicate window to establish radiation limits for an acceptable darkening level. The results verified that most of the films would be unusable when returned to earth, and that the borosilicate window would be darkened beyond allowable limit, unless additional protection was provided. The operational solutions to these problems involve protecting the film with five film vaults and protecting the window with a radiation shield. The largest vault is made of aluminum and weighs over 2000 lb (its thickest compartment wall is 3.4 in.). The window radiation shield is a light honeycomb structure which is swung away for limited astronaut viewing or when the S190 experiment is in operation. Although the shield is light weight, it is heavy enough to stop the large number of low energy electrons making up a major part of the external environment and which are potentially damaging to the window. The paper contains a brief description of the Skylab mission and some of the associated experiments. The radiation environment the spacecraft will encounter is discussed. The results of the radiation test programs on Skylab photographic film and on borosilicate glass are presented. Operational solutions to the two problems of excessive film fog and loss of transmittance through the glass are described.

SKYLAB MISSION

Skylab is an experimental space station program of the National Aeronautics and Space Administration, designed to expand our knowledge of manned earth orbital operations and to accomplish carefully selected scientific, technological, and medical investigations. This space station is to be made up of a cluster of individual modules including a Saturn IVB stage modified into an Orbital Workshop (OWS), an Airlock Module (AM), a Multiple Docking Adapter (MDA), a Saturn V Instrument Unit (IU), an Apollo Telescope Mount (ATM), and an Apollo Command and Service Module (CSM).

Flight 1 of the Skylab mission will begin with the launch from the Kennedy Space Center (KSC) of all modules except the CSM. These modules will be inserted by a Saturn V into a circular orbit 235 n mi high, inclined 50° with respect to the equator. Within the 7.5 hr lifetime of the IU, the orbital assembly will be oriented to a solar inertial (sun pointing) attitude mode, and the workshop solar array will be deployed. The ATM will be rotated 90° from the launch position, and the ATM solar arrays will be deployed. The ATM pointing control system will be activated to maintain the solar-inertial attitude. The interior of the OWS, AM, and MDA will be pressurized to 5 psia with an oxygen-nitrogen atmosphere, making it ready to accept docking of the CSM and entry of the flight crew.

Flight 2 will be launched from KSC one day after Flight 1, using a Saturn IB. A CSM with a three-man crew will be inserted into an interim orbit. The CSM will rendezvous with the orbital assembly, using the service propulsion system to boost it to the required 235-n-mi-orbit, and will dock to the axial port of the MDA, thus completing the cluster (Fig. 1). The crew will enter the workshop and complete activation of the orbital assembly for habitation. For the remainder of the Flight 2 mission, the experiment program will be conducted with emphasis on the medical experiments and evaluation of the habitability systems. The ATM experiments will be activated and their operation verified. Nominally, the CSM will deorbit on the 28th day, and splashdown is planned in the West Atlantic recovery area.

Flight 3 involves the launch of a second crew on a Saturn IV approximately 80 days after the launch of Flight 2. The orbit-insertion, rendezvous, and docking procedures will be the same as those for Flight 2. The mission will be similar to Mission SL-1/SL-2, except that it will be open ended for up to 56 days duration. In addition, more emphasis will be placed on the solar astronomy experiments. Assuming nominal mission duration and deorbit, recovery is planned in the mid-Pacific recovery area.

Flight 4 will be launched approximately 100 days after the launch of Flight 3. Its payload is the third CSM and crew. This mission will complete the planned experiment objectives, and will provide additional statistical data on the space crew's adaptability and performance over the planned 56-day mission. Recovery will be in the mid-Pacific.

EXPERIMENTS

Approximately 60 experiments, to be carried out during the 240-day lifetime of Skylab, have been divided into the six general categories of solar astronomy, science, biomedical, technology, earth resources, and crew operations. Of these, the solar astronomy, science, and earth resources
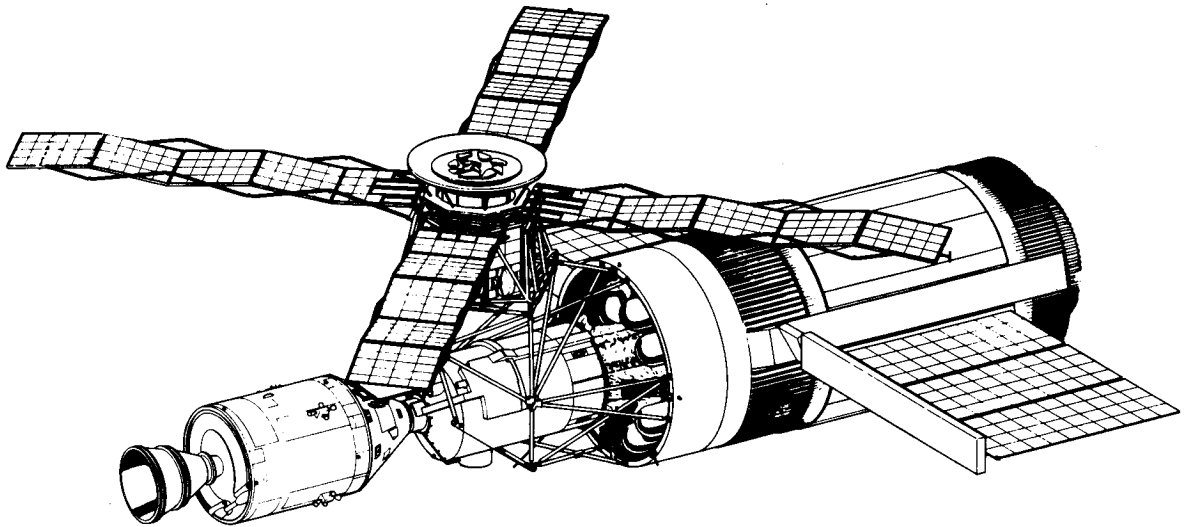
FIGURE 1.-Skylab Cluster

experiments are of most interest here because of the corpuscular radiation problems associated with them.

The solar astronomy scientific experiments comprise the payload for the ATM. These instruments are the largest, most complex ever designed for performing solar research from an orbiting spacecraft, and all but one use some type of photographic film to record their data.

The science experiments are designed to study the discipline areas of geophysics, physics of the upper atmosphere, physics of the interplanetary medium, solar studies to supplement the ATM experiments, and both galactic and intergalactic astronomy. Many of these experiments use extremely sensitive photographic film to record their data.

The earth resources experiments (EREP) are designed to support the development of sensors and applications technology, required for the design of operational spacecraft systems. These experiments are mounted both on the interior and exterior of the MDA. One EREP experiment, S190, uses a six-camera array with synchronized shutters looking through a 1.6-in.-thick borosilicate window to take pictures of the earth's surface. This window is the highest quality of any put into space to date. Even though an electroconductive coating is used on the outside surface of the glass to resistively heat it, transmittance must be at least 0.65 at a wavelength of 0.40 μm, at least 0.70 at a wavelength of 0.45 μm, at least 0.77 from 0.50 to 0.70 μm, and at least 0.63 at a wavelength of 0.90 μm.

RADIATION ENVIRONMENT

A predicted radiation environment has been calculated, using the Martin Marietta computer code PD-202, which determines positions in the trajectory at specified intervals and converts these data to the corresponding McIlwain geomagnetic coordinates (B, L) (ref. 1). The electron and proton fluxes and energy spectra are then determined from the Vette AP-1, 5, 6, 7 and AE-2, 1968, environments (refs. 2 and 3). Since the Skylab orbit repeats essentially every 24 hr, calculations were for an average daily differential spectrum (Fig. 2 and 3) and a typical daily flux history (Fig. 4). It can be seen from Fig. 4 that, in this particular orbit, Skylab passes in and out of the Van Allen belt periodically and, in fact, completely misses the South Atlantic anomaly five orbits in a day. An indication of the hardness of the proton spectrum can be seen from Fig. 5, which was generated by Martin Marietta computer code KD-205. This program uses the spectrum compiled by PD-202 and the stopping power data of Berger and Seltzer (ref. 4) to calculate the dose at the center of a sphere, of specified thickness, both in rems and in rads.

Additional doses, at various points in the cluster, have been calculated by Hill et al. (ref. 5), taking into account the specific geometry of each module and intermodule shielding. These calculations also used the spectrum generated by PD-202 and are shown in Fig. 6. Examining the values in this figure and using Fig. 4 as a rad-to-rem

DIFFERENTIAL PROTON SPECTRUM

AP-7

FLUX (particles/cm²-mev-day)

Note: 1. 235-nautical miles circular orbit.
       2. 50° inclination.

ENERGY (mev)
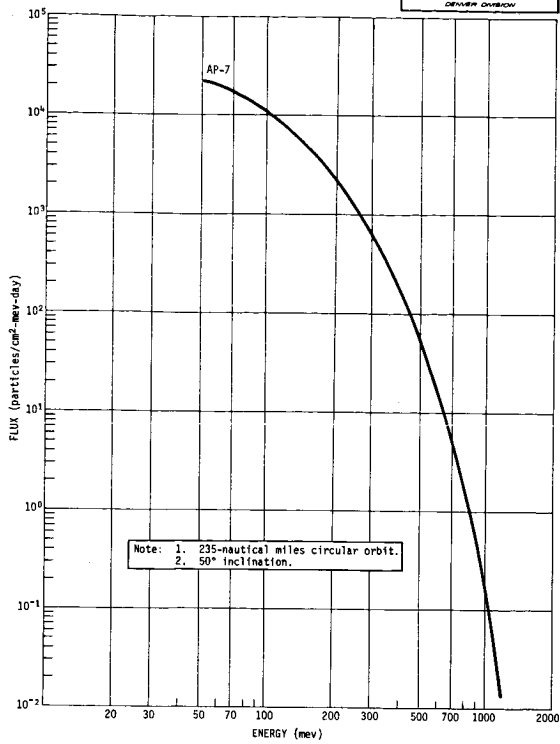
FIGURE 2.-Differential proton spectrum.

TYPICAL DAILY PROTON FLUX HISTORY

Time (hours)
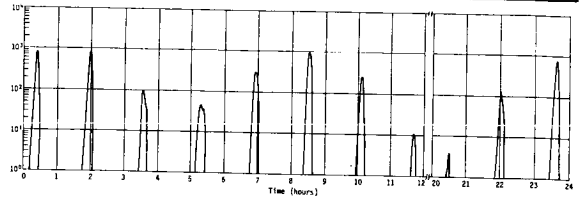
FIGURE 4.-Typical daily proton flux history.

DIFFERENTIAL ELECTRON SPECTRUM

FLUX (particles/cm²-mev-day)

Note: 1. 235-n-mi circular orbit.
       2. 50° inclination.

AE-2, 1968

ENERGY (mev)
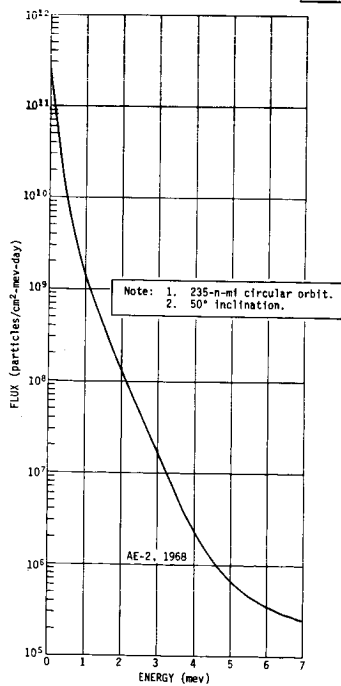
FIGURE 3.-Differential electron spectrum

EFFECT OF SHIELDING ON DOSE AT 235-N-MI CIRCULAR ORBIT,
50° INCLINATION

RADS
MUSCLE   REMS

DOSE/DAY
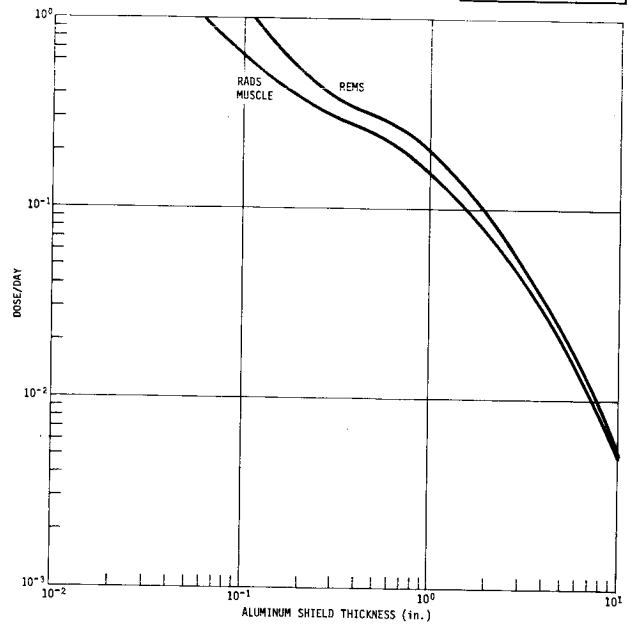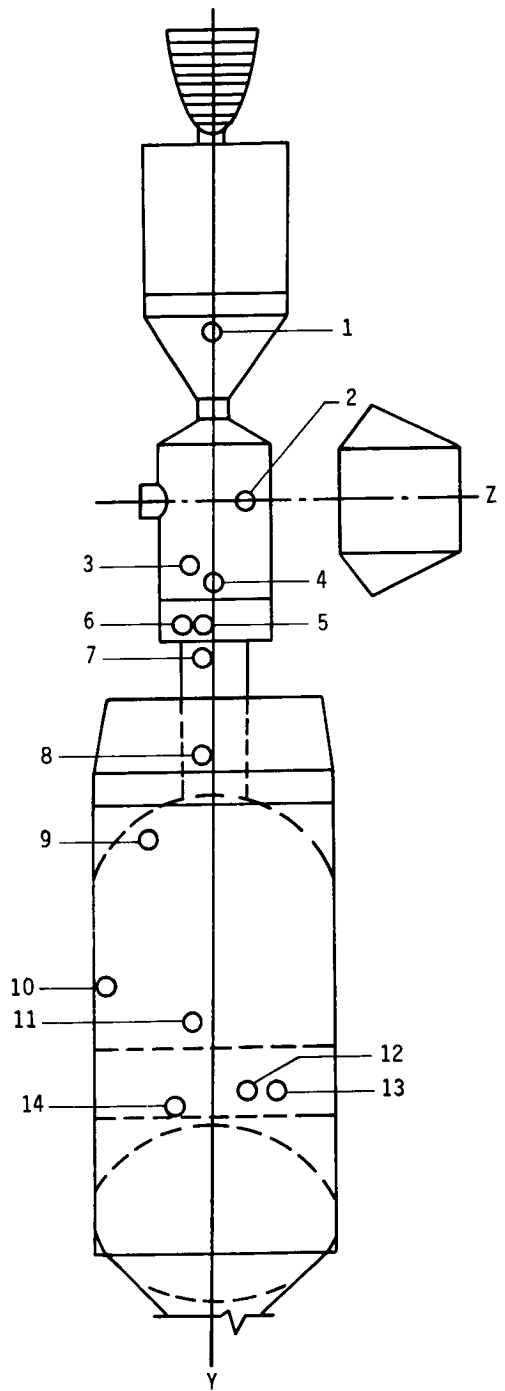
ALUMINUM SHIELD THICKNESS (in.)

FIGURE 5.-Effect of shielding on dose at 235-n-mi circular orbit, 50° inclination.

Location	Dose/Day (Rads-Air)
1	0.05880
2	0.13119
3	0.15111
4	0.15110
5	0.13936
6	0.13090
7	0.06236
8	0.05039
9	0.23846
10	0.20660
11	0.13563
12	0.12226
13	0.14284
14	0.15298

FIGURE 6.-Radiation doses at various points inside Skylab Cluster.

converter, it becomes evident that additional radiation shielding for the Skylab crewman is unnecessary because NASA's planning operational dose for a 56-day Skylab mission is 250 rems to the skin and 25 rems to the blood forming organs.

Cosmic radiation also makes up part of the radiation environment to be encountered by Skylab. Although unimportant when considering surface doses outside the orbital assembly, this environment can become significant behind very heavy shields, such as film vaults, because of the greater range of cosmic rays compared to the range of Van Allen belt protons and electrons. Burrell et al. (ref. 6), estimate that behind a 10 gm/cm^2 aluminum shield, the total cosmic ray dose at 240 n mi, 50°, will be 2×10^{-3} rads/day, or 0.4 rads to a film stored 200 days.

RADIATION TEST PROGRAMS

Photographic Film

A radiation test program was conducted by Martin Marietta's Denver Division to obtain film degradation data for establishing minimum radiation shielding requirements of the experiment and operational films to be used in the Skylab mission (ref. 7). The films were irradiated at various levels with Cobalt-60 gamma rays and then imaged in selected regions of the X-ray, ultraviolet, visible, and near infrared to simulate spectral ranges in which the films will be used. Sensitometric analysis of the processed film included Hurter and Driffield (H&D) curves, film base plus fog, gamma, and modulation plots. A series of principal investigator reviews were conducted to allow each principal investigator (PI) to render a subjective judgment of the maximum acceptable radiation dosage for the film types to be used on his experiment. This was done by visual inspection of the irradiated film samples. Results of the sensitometric analysis and PI evaluations were combined to form the Martin Marietta-recommended acceptable radiation dose levels for the various film types presented in Table 1.

Most of these films are to go into orbit in the OWS or MDA on Flight 1, even though they may be used on Flights 3 or 4. This results in the majority of the film being stored in orbit for several months (81 to 210 days). From Figure 5, the corresponding radiation dose would be 12.5 to 31.5 rads in the MDA and 9.7 to 25.2 rads in the OWS. Comparing these values with the data in Table 1, it is obvious that most of the film would be fogged beyond use before it was put into a camera, unless specific protective measures were taken.

S190 Borosilicate Window

A second radiation test program was conducted at the Lawrence Radiation Laboratory: (1) to quantify the darkening effect of electron fluence on borosilicate BK-7 glass; (2) to determine whether the electroconductive coating on the outer surface of the glass would be subject to degradation by the radiation environment; and (3) to determine if a static discharge of the trapped electrons, and resultant Lichtenberg figure, would be possible at the expected fluence levels (the

TABLE 1.-Recommended acceptable radiation dose levels for various Skylab photographic films.

Film Type	Experiment Numbers	Recommended Acceptable Rad Dose
OWS Vaults:		
S0166 (2485)	S063, S073, T025, T027	1
S0180	S190	1
	M479	2
SC-5	S019, S020	1.5
103-0, UV	S063	2
S0121 - Color	S190	2
S0246 (2424)	S190	2
S0168	M151	3
	M507, M508, M509, T013, T020, Oper.	4
2403	T025, T027	4
5242 EFB - Color	M512	8
103a-F	T027	8
I-N Spectroscopic	S190	8
3400	S190	8
3401	(Formerly considered for S190)	8
S0368 - Color	D021, Operational	8
MDA Vaults (ATM Film):		
S0114	S054, S056	8
104-01 (SWR)	S082 A & S082 B	8
3400	S052, S054	16
	S082 A & S082 B	32
S0392	H-Alpha 1	32

latter effect was noted by the National Bureau of Standards (ref. 8) in tests performed on a similar borosilicate glass, BK-7G). Samples of the glass were exposed to a spectrum of electrons which had a maximum energy of 2.5 mev. After irradiation, the glass surface was struck with a grounded point in an effort to discharge the sample. No Lichtenberg figures were observed in any of the samples and it was assumed that the strength of the glass was unchanged since there were no cracks. However, additional tests are planned later this year to measure bending strength of an irradiated sample.

Transmittance was measured both before and after irradiation. The results are shown in Fig. 7 and 8, along with the required level of transmittance. Clearly, the window could not fly the entire Skylab mission of 250 days unprotected, and still be within the required specification of transmittance, since the expected external electron flux is approximately 5×10^{10} electron/cm^2/ day.

OPERATIONAL SOLUTIONS

Excessive Film Fog

Prediction of the amount of radiation-induced fog that a particular film will acquire is based on a number of factors: storage location, length of time in storage, experiment (camera) location, length of time in camera, etc. The need for additional protection for a film is determined by the difference between the maximum acceptable dose (Table 1) and the dose to be received during operation of the experiment. If the dose received during storage is larger that this difference, a film vault is necessary. During the Skylab missions, even though most of the photographic film is to be launched with the workshop on Flight 1, each load is to return at the end of the flight on which it is used. Consequently, each load of film has different protection requirements, even though it is the same film used in the same experiment.

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FIGURE 7.-Transmittance of irradiated uncoated samples of BK-7 borosilicate glass.
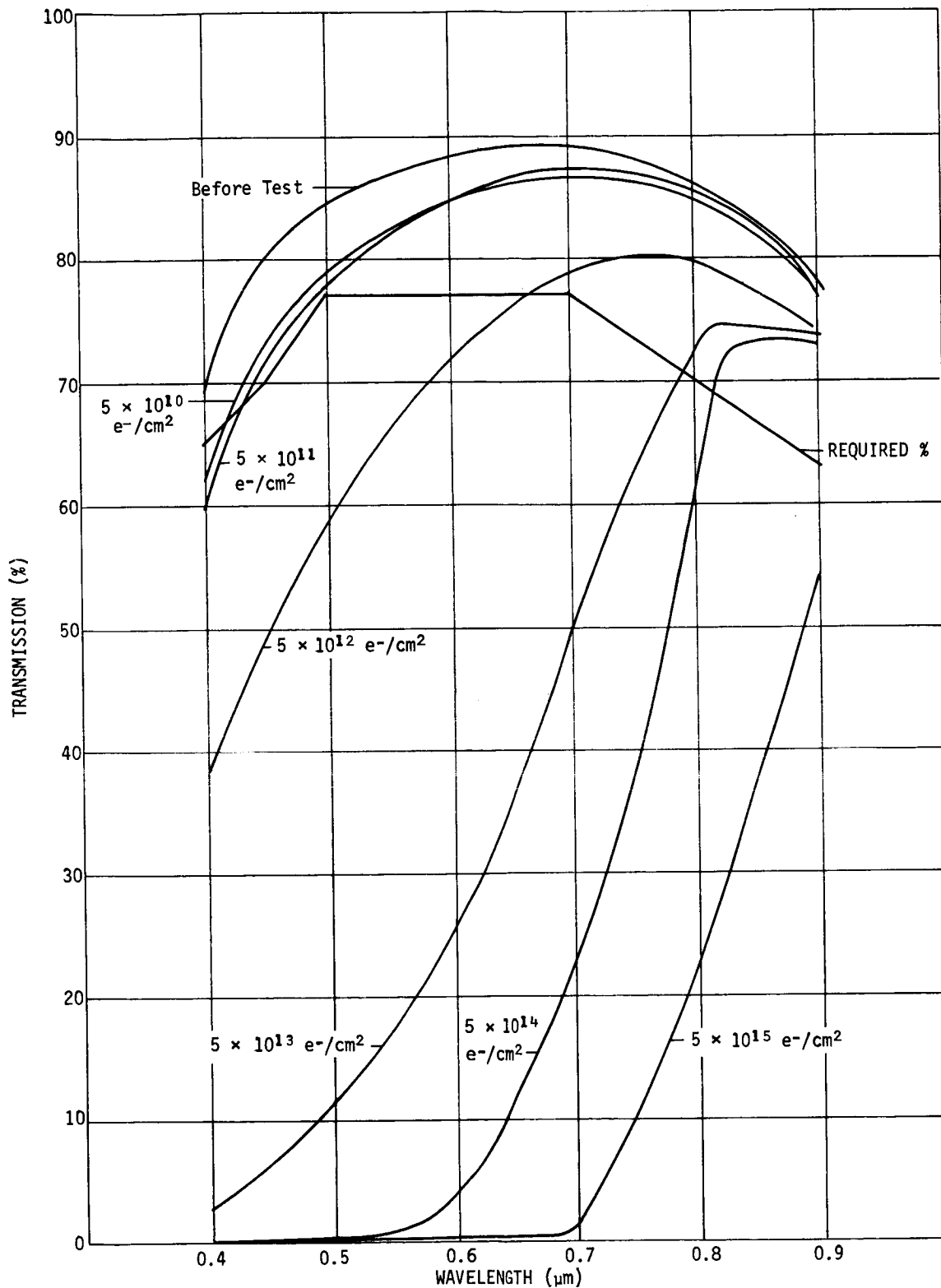
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FIGURE 8.-Transmittance of irradiated coated samples of BK-7 borosilicate glass.

Taking into account these factors and the mission requirement that all ATM experiment film must be stored in the MDA, and the structural requirement that no more than 500 lb could be mounted on any one longeron, resulted in four separate film vaults in the MDA. All vaults are made of aluminum, ranging in thickness from 0.09 to 1.5 in., and weigh a total of 1545 lb empty. They were designed and built by Martin Marietta's Denver Division.

All other films are to be stored in the OWS. Since this module is capable of supporting a larger concentrated weight, only one vault with several compartments of various thicknesses was required. This, of course, is a more efficient design method, since one compartment shields the next and reduces total amount of material need. Even so, this vault weighs 2398 lb empty and requires a pallet to stand on to distribute its weight over the floor of the OWS. It is made up of four aluminum compartments whose thicknesses are 0.25, 1.9, 2.9, and 3.4 in. This vault was designed in the Astronautics Laboratory of the Marshall Space Flight Center and is being built by McDonnell Douglas' Western Division.

With the addition of these five film vaults, at a total weight penalty of almost 4000 lb, all photographic film should return with usable data.

Darkening of the S190 Borosilicate Window

Since the electron environment that the window will see is made up mostly of low energy particles, a lightweight shield is all that is needed to provide adequate radiation protection against darkening. Consequently, the current window cover design involves a honeycomb structure with 0.028-in. fiberglass face sheets. In addition to shielding the glass from radiation damage, the window cover also serves as a meteoroid shield to stop meteoroid erosion; a thermal shield to allow the window and frame heaters to stabilize the temperature of the glass (when desired for optical reasons); and a contamination shield to prevent contaminates from depositing on the window. A simple opening mechanism allows the astronaut to swing the shield away when he desires to operate the S190 experiment.

SUMMARY

An experimental space station, Skylab, is to orbit the earth during 1973 in a 235-n-mi-circular orbit inclined 50°. During its operational lifetime of approximately 238 days, three three-man crews will rendezvous with Skylab and carry out various experiments up to 56 days before returning.

The expected radiation environment Skylab will see is made up of protons and electrons from the Van Allen belt, and of cosmic rays. The large number of electrons are mostly low energy particles that result in a high surface dose, but add little to the internal dose. This high electron fluence to the outside surface of a borosilicate window used by one of the experiments could cause darkening of the glass. The dose inside Skylab (due mainly to protons), although not a problem for the astronauts, is a problem for photographic film used by some of the experiments. The dose from cosmic rays is very low and does not become significant until very heavy structures, such as film vaults, are considered.

Two radiation test programs were run to quantify maximum acceptable film fog for each type film to be used and maximum acceptable window darkening. Since the expected environment would exceed these limits, five film vaults and a removable window cover were incorporated into the Skylab design, at a weight penalty of almost 4000 lb, to insure that useful data would be returned at the end of the mission.

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