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Geometry and Mass Model of Ionizing Radiation Experiments on the LDEF Satellite

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1. Introduction

1.1 Purpose

Extensive measurements related to ionizing radiation environments and effects were made on the Long Duration Exposure Facility (LDEF) satellite during its mission lifetime of almost six years, as summarized in Ref. 1. These data, together with the opportunity they provide for evaluating predictive models and analysis methods, should allow more accurate assessments of the space radiation environment and related effects for future missions in low Earth orbit.

The LDEF radiation dosimetry data is influenced to varying degrees by material shielding effects due to the dosimeter itself, nearby components and experiments, and the spacecraft structure. For example, data for the absorbed dose from geomagnetically trapped protons indicate a strong anisotropy for measurements made at different locations on LDEF[2], and measured LET (linear energy transfer) spectra from galactic cosmic rays also exhibit a directional response[3]. A question in interpreting these results is to what extent this angular response is due to the directionality of the space radiation environment, which would be common to other spacecraft having attitude and orbit parameters similar to LDEF, as opposed to the influence of shielding variations particular to the LDEF experiment/spacecraft configuration. As another example of the influence of spacecraft shielding on LDEF data interpretation, in astrophysics experiments of the composition and origin of heavy ions in the space environment the direction of incident ions is used to determine whether the ions are of galactic origin or from radiation trapped in the geomagnetic field. In some experiments[4], an appreciable flux has been observed coming from directions corresponding to the interior of LDEF, and the issue here is the magnitude of the spacecraft shielding effects on the observed directionality and energy spectra.

The purpose of the work here is to generate a geometry and mass model of LDEF incorporating sufficient detail that it can be applied in determining the influence of material shielding on ionizing radiation measurements and predictions. This model can be utilized as an aid in data interpretation by "unfolding" shielding effects from the LDEF radiation dosimeter responses.

Utilization of the LDEF geometry/mass model, in conjunction with predictions and comparisons with LDEF dosimetry data currently by underway[5], will also allow more definitive evaluations of current radiation models for future mission applications. Comparisons of predicted absorbed doses with LDEF experiments based on simple shielding distributions (one-dimensional slab and sphere) show substantial differences (a factor of two or more)[6]. While simple one-dimensional shielding geometries are commonly used for scoping estimates of certain radiation dose effects where factors of two uncertainty are acceptable (e.g., preliminary hardware design), in many situations (predictions of astronaut dose, component lifetimes due to radiation damage, etc.) better accuracy is required. Although these differences between scoping predictions and the LDEF measurements could be influenced by several factors (external environment uncertainties, approximations in radiation transport and particle interaction phenomenology, etc.) in addition to shielding, it should be straightforward to separate the effects of shielding using the LDEF spacecraft model developed here.

1.2 Scope

Initial work on the development of a LDEF geometry/mass model, which included the spacecraft structure and individual experiment trays but provide no detailed modeling of the tray contents, has been reported earlier[7]. The emphasis of the present work is on extending the model to include a detailed description of the contents of several trays. The trays considered for detailed modeling are F2, F8, and H3 and H12, which have locations on LDEF as indicated in Fig. 1-1.

The rationale of this tray selection for detailed modeling is as follows: Tray F2 (containing Exps. P0004 and P0006) is located near the trailing edge of LDEF, and the radiation dose measurements made from this tray are expected to be near the maximum expected from consideration of the anisotropy of the trapped proton exposure. Conversely, Tray F8 is located

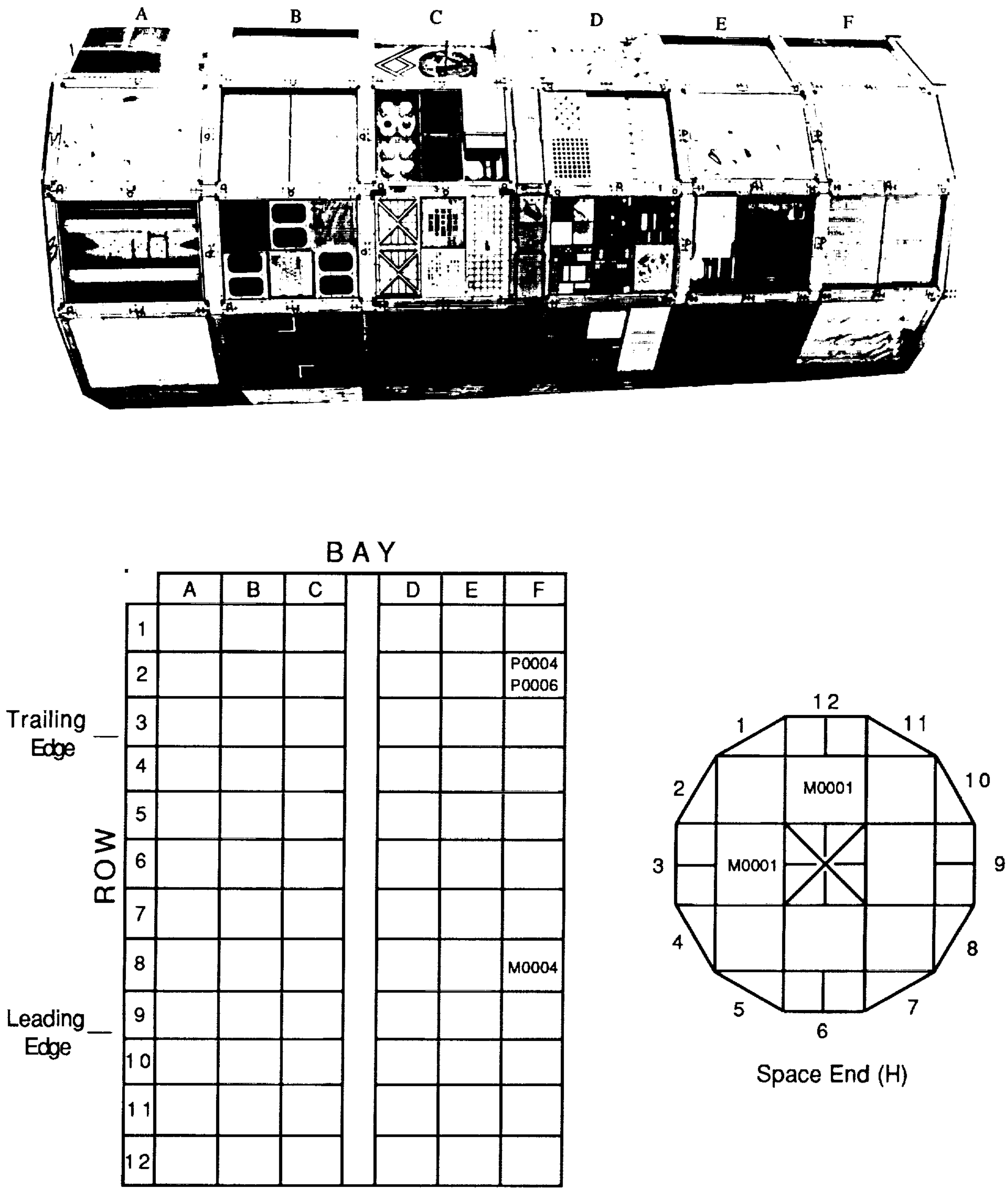


Fig. 1-1. Locations of experiment trays (F2, F8, H3, H12) and radiation dosimetry experiments (P0004, P0006, M0004, M0001) modeled in present work.

near the LDEF leading edge, so the dose measurement by Exp. M0004 in this tray should be representative of the minimum trapped proton exposure. Since measurements in these two trays are particularly applicable in evaluating current environments models describing the directionality of satellite exposure to trapped protons, it is important to take into account the details of shielding variations around the dosimetry to evaluate shielding vs. exposure directional effects. Furthermore, other measurements from the P0006 experiment in Tray F2 show a directional dependence of the LET spectra from heavy ions in galactic cosmic rays[3], and shielding variations around this experiment are needed in interpreting the data. Preliminary data from Experiment M0001 in Trays H3 and H12 indicate a higher heavy ion flux than expected entering the detector from the direction of the interior of the LDEF spacecraft[4], and the influence of shielding on relating the observed ion spectra to the incident space spectra is of interest in interpreting these data.

The general modeling approach is discussed in Sec. 1.3, and details of the modeling for Experiments P0004, P0006, M0004, and M0001 are given in Secs. 2-4. As part of checking the geometry model, some preliminary 3-D shielding calculations and comparisons with absorbed dose measurements has been made and some example shielding distributions generated, and these results are given in Sec. 5.

1.3 Methodology

The LDEF geometry/mass model has been programmed in FORTRAN using the combinatorial geometry methodology of describing complex three-dimensional configurations. The computer version of the geometry module used here has been operated for many years in radiation transport applications, and is the geometry module commonly used with the HETC transport code.

The combinatorial geometry ("com-geom") method describes three-dimensional material configurations by applying logical operators to form unions, differences, and intersections in combining simple solid bodies (spheres, boxes, cylinders, etc.) to form a complex geometry.

Material properties are assigned to each zone defined by these operators, and ray-tracing algorithms are included to provide the pathlength and material identifier for each zone traversed. This material identifier is used as an index to retrieve information (density, atomic compositions, etc.) from a materials properties table. As an aid in debugging, we have used the SABRINA code[8] to obtain a graphical output of the geometry input data.

Input Data Sources

Input data for constructing the LDEF geometry/mass model has been obtained from engineering drawings, preflight reports from experimenters describing component layouts, dimensions, and materials for individual experiments, and pre- and post-flight photographs, all kindly provided by the LDEF Project Science Office[9]. Key modeling input was the weight of individual experiment trays and all spacecraft structural components provided by NASA LaRC from pre-flight center-of-mass and flight dynamics analyses[10]. Dimensions for the experiment trays and descriptions of certain electronics and data storage components common to various experiments were obtained from the LDEF Experimenter Users Handbook[11]. General descriptions and photographs of individual experiments from Clark, et al.[12] were also helpful.

Information needed for the detailed modeling of Exps. P0004, P0006, and M0004 were obtained from reports by Benton, et al.[13-16] with supplemental information provided by Frank[17]. A detailed description of Exp. M0001 was provided by Tylka and Adams[18].

Level of Detail Incorporated.

The LDEF spacecraft is considered to be comprised of the following general categories for modeling purposes: spacecraft structure, miscellaneous spacecraft components, and experiments, which includes the experiment trays and components (Table 1-1). The 84 experiment trays on LDEF can be further divided into four subcategories: (a) space debris experiments (26 trays), for which the tray contents can be adequately modeled as an aluminum plate; (b) ultra-heavy cosmic ray experiments (16 trays), for which the contents can be simply modeled as aluminum plus

Table 1-1(a). Level of detail for modeling LDEF spacecraft.

Category	Component	No. Places	Weight (lbs.)	Weight %	Modeling Approach
STRUCTURE	Center Ring	1	2,073	9.7%	Modeled as individual component.
	Longerons	24	2,280	10.7%	Modeled as individual components.
	End Frames	2	1,374	6.4%	Modeled as individual components.
	Diagonal Tubes	8	926	4.3%	Modeled as individual components.
	Intercostal Rings	72	758	3.5%	Modeled as individual components.
	Trunions,Pins,Scuff Plts	10	501	2.3%	Modeled as individual components.
	End Support Beams	5	285	1.3%	Modeled as individual components.
	TOTAL STRUCTURE:		8,197	38.3%	
MISCELLANEOUS	Batteries	2	100	0.5%	Included as part of earth-end support beam.
	Initiate Electronics	1	105	0.5%	Included as part of center ring weight.
	Wiring	-	100	0.5%	Included as part of center ring weight.
	Nuts and Bolts	-	200	0.9%	Included as part of center ring weight.
	Damper Assembly	1	62	0.3%	Modeled as individual component.
	Thermal Covers (Ends)	12	154	0.7%	Modeled as individual components.
	Ballast Plates	11	365	1.7%	Included as part of end frames.
	TOTAL MISCELLANEOUS:		1,086	5.1%	
EXPERI-MENTS	Experiment Components and Trays	84	12,110	56.6%	Modeled each experiment tray separately, with individual experiment weights preserved. Modeling for components varies with experiment type.
	TOTAL LDEF WEIGHT:		21,393	100.0%	

Table 1-1(b). Level of detail for modeling experiments.

No. Trays	Model	Experiments
26	Al plate	S0001: Space Debris (LaRC)
16	Al+plastic plates	A0178: Ultra-heavy Cosmic-Ray Expt. (Dublin Inst., ESTEC)
13	"detailed"	Selected experiments containing ionizing rdiation dosimetry.
29	homogenized Al	(all others)

Table 1-1(c). Trays containing ionizing radiation dosimetry.

Tray Bay-Row	Experiment No.	Experiment	Dosimetry
C-2, G-2	A-0015	Biostack (DFVLR)	TLD's, PNTD's
C-3, C-9	A-0114	Atomic Oxygen (UAH, MSFC)	Activation Samples
B-3	A-0138	Optical Fibers (CERT/ONERA - DERTS)	TLD'S
H-3, H-12	M0001	Heavy Ions (NRL)	PNTD's
D-3,D-9,G-12	M0002-1	Trapped Proton Spect. (AFGPL,MSFC, et al.)	PNTD's,TLD's,Act.
E-6	M0002-2	Heavy Cosmic-Ray Nuclei (U. Keil)	PNTD's
D-3,D-8,D-9	M0003	Space Envr. Effects on Matls. (Aerospace)	TLD's
F-8	M0004	Space Envr. Effects on Optics (AFWL)	TLD's, PNTD's
C-2	M0006	Space Envr. Effects (AFTAC, Grumman)	TLD's
F-2	P0004	SEEDS (Univ. SF)	TLD's, PNTD's
F-2	P0006	LET Spectrum Meas. (Univ. SF, MSFC)	TLD's, PNTD's, Fiss. & Act. Samples

plastic; (c) trays containing ionizing radiation dosimeters (13 trays), for which some detailed modeling of the tray components is desirable, and (d) all other experiments (29 trays), for which the tray is considered to be filled with aluminum having a reduced density such that the individual tray weight is preserved. Thus, each individual experiment tray is modeled, with the actual weights of the trays and contents included, but only the contents of selected trays are modeled in detail for assessing shielding effects on the radiation dosimeter responses. Of the 13 trays indicated in Table 1-1 as containing ionizing radiation dosimetry, four trays (F2, F8, H3 and H12) are modeled here in detail.

Figure 1-2 shows a view of the LDEF geometry model including the four detailed experiment trays modeled in the present work.

1.4 Potential Applications

The LDEF geometry module program can be applied in several operational modes, as illustrated in Fig.1-3. As a standalone program, material thicknesses along rays emanating from specified spatial points and a specified angular grid can be generated to provide three-dimensional shielding variations around various dosimetry components. Such shielding distributions can also be used as input to one-dimensional transport codes which use solid angle sectoring to approximate three-dimensional radiation transport. Also, the geometry module can be interface with detailed three-dimensional Monte Carlo radiation transport codes such as HETC.

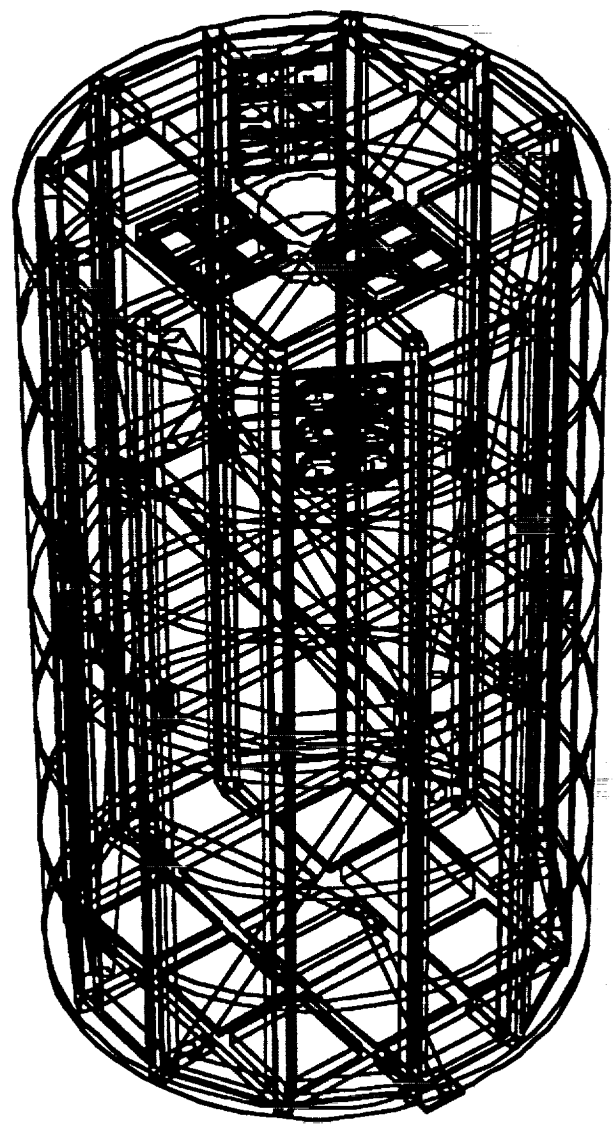


Fig. 1-2. Combinatorial geometry model of LDEF spacecraft with the four experiment trays (F2, F8, H3, and H12) modeled in detail in the present work.

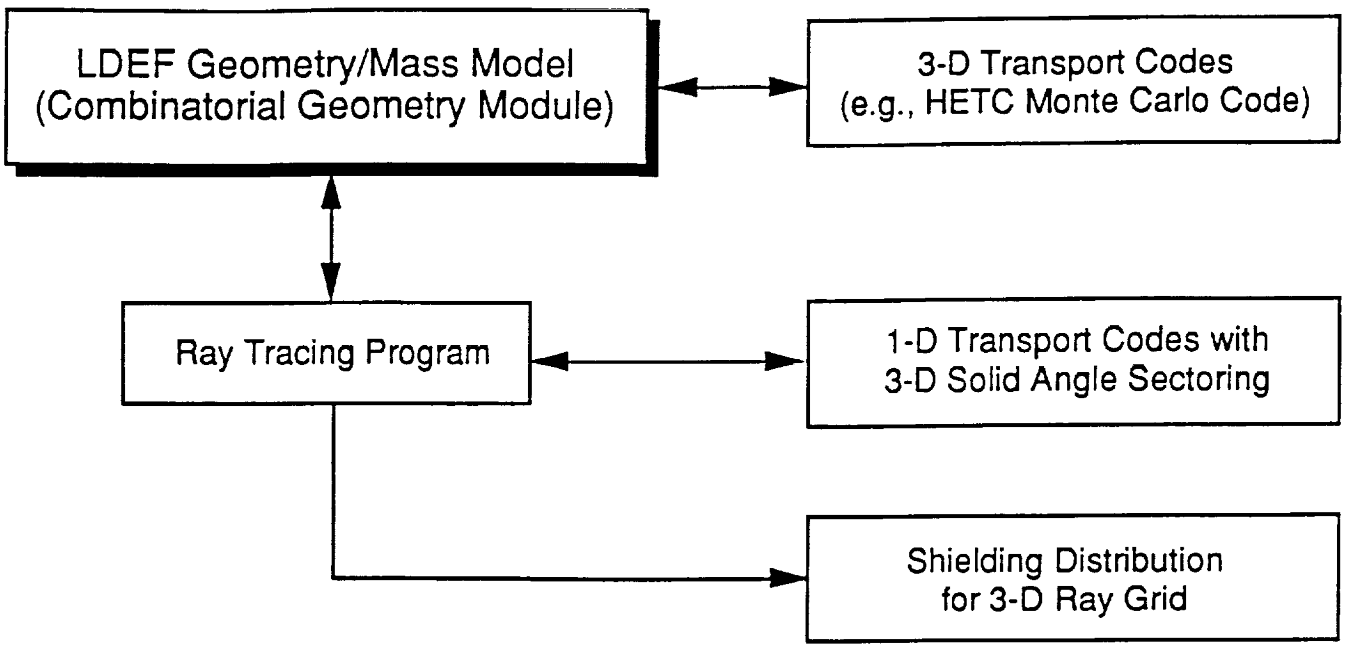


Fig. 1-3. Different operational modes for utilizing the LDEF geometry/mass model.

2. Modeling of Dosimetry Experiments P0004 and P0006

Experiments P0004 and P0006 are located in Tray F2 near the leading edge of LDEF. Experiment P0004 consists of six 12 inch-diameter canisters containing tomato seeds for the Space-Exposed Experiment Developed for Students (SEEDS)[19], designated as Exp. P0004-2, and a smaller canister contained the Seeds in Space Experiment (Exp. P0004-1)[20]. The SEEDS canisters contained radiation dosimeters comprised of thermoluminescent detectors (TLDs) and plastic nuclear track detectors (PNTDs) with the Univ. San Francisco group of Benton, et al. as principal investigator.

Tray F2 also included a canister containing a dosimetry package for the Linear Energy Transfer Spectrum Measurement Experiment (LETSME)[21], designated Exp. P0006, with E. V. Benton of Univ. San Francisco and T. A. Parnell of the NASA Marshall Space Flight Center as principal investigators. The P0006 dosimetry contained several types of detectors (TLDs, PNTDs, activation materials, and neutron detection foils), as described in detail later in this section.

2.1 Experiment Tray Model

The P0004 and P0006 experiments are contained in one of the standard 6-inch deep aluminum peripheral trays used on LDEF. Actual tray geometry and dimensions are shown in Fig. 2-1. The tray model (Fig. 2-2) assumes perpendicular rather than slanted tray sides and approximates the angle and channel type support braces as bars of rectangular cross-sectional area having reduced aluminum density to preserve the weight of each brace.

2.2 Canister Models

The layout of canisters in the experiment tray is shown in Fig. 2-3. The P0006 and P0004-1 canisters are of cylindrical shape with a flange for attaching the top and bottom. The model for the P0006 canister is shown in Fig. 2-4, and the P0004-1 canister was modeled

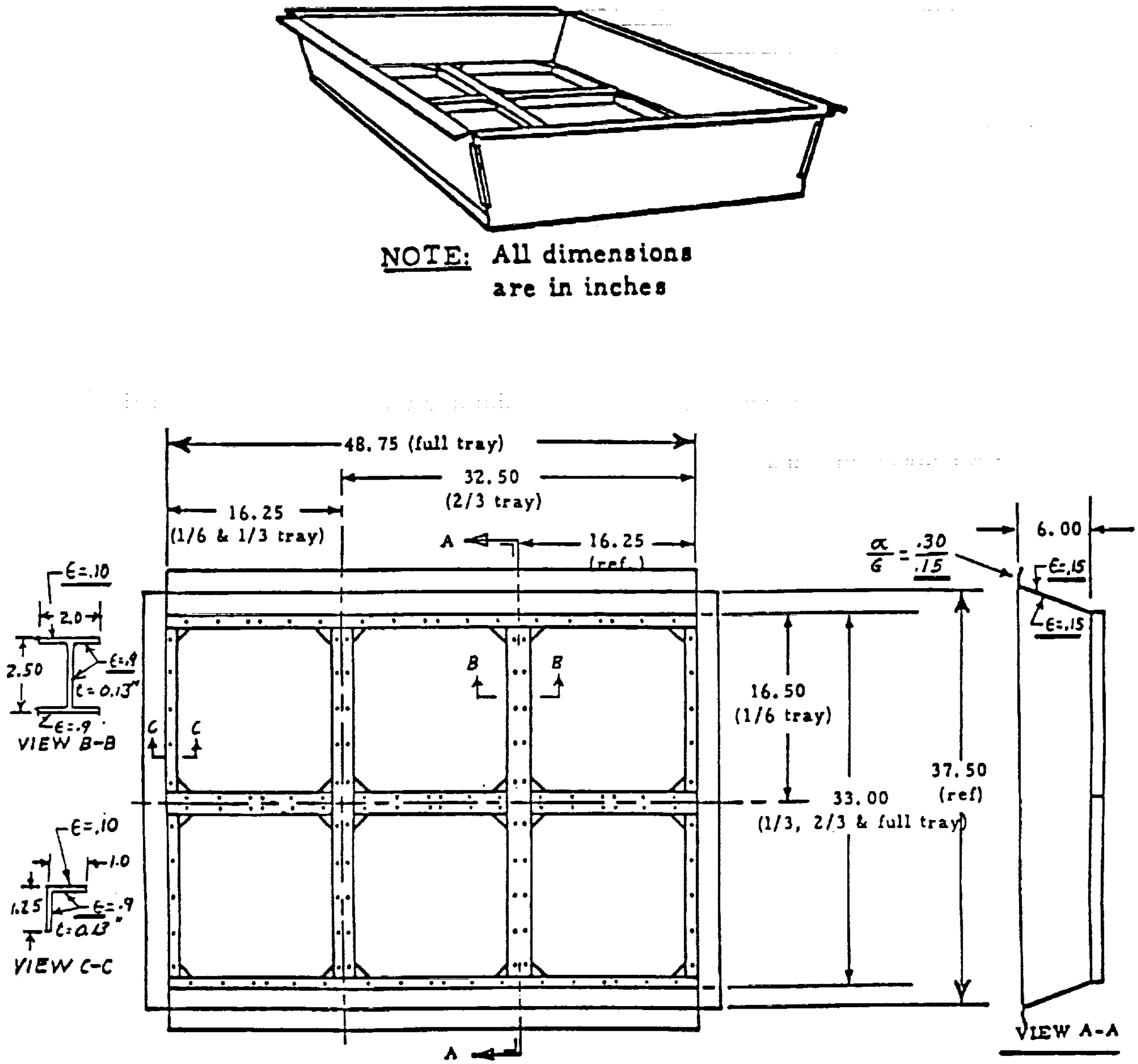


Fig. 2-1. LDEF experiment tray dimensions for 6-inch deep trays deployed on sides of spacecraft.

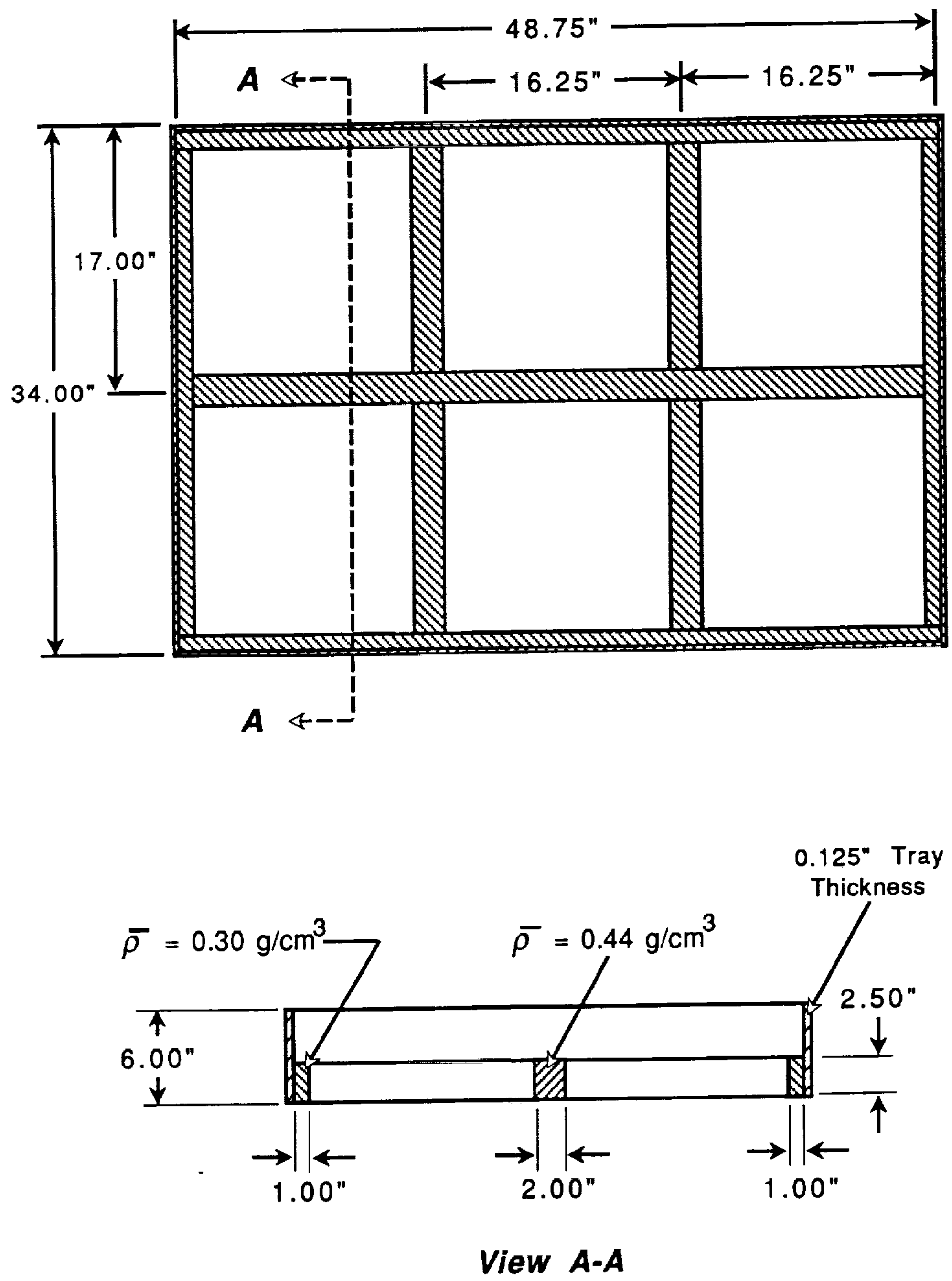
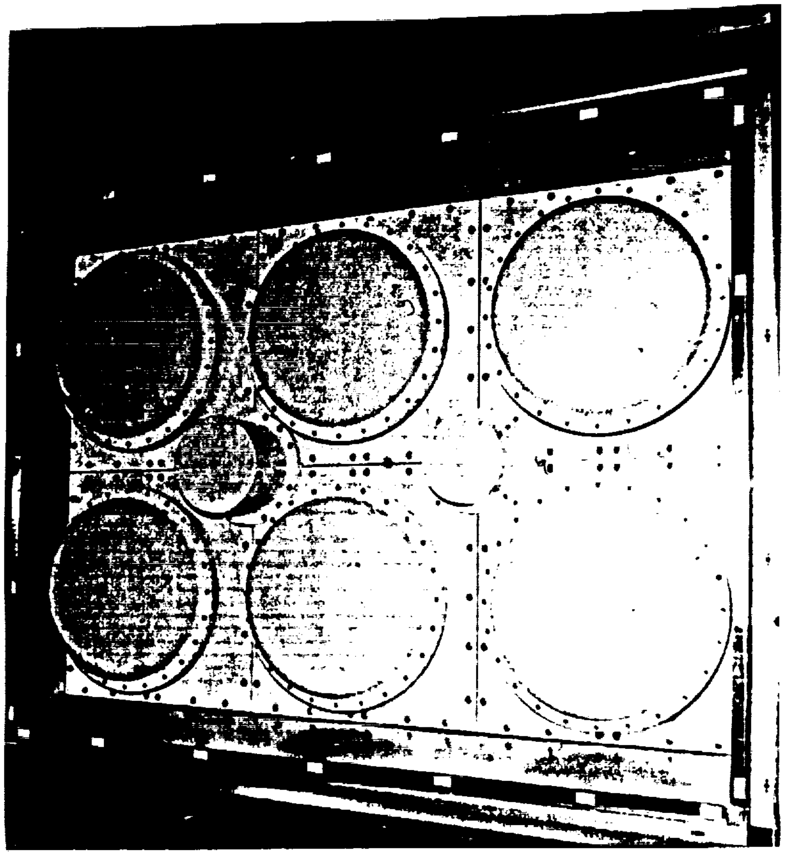


Fig. 2-2. Assumptions for modeling LDEF Tray F2.



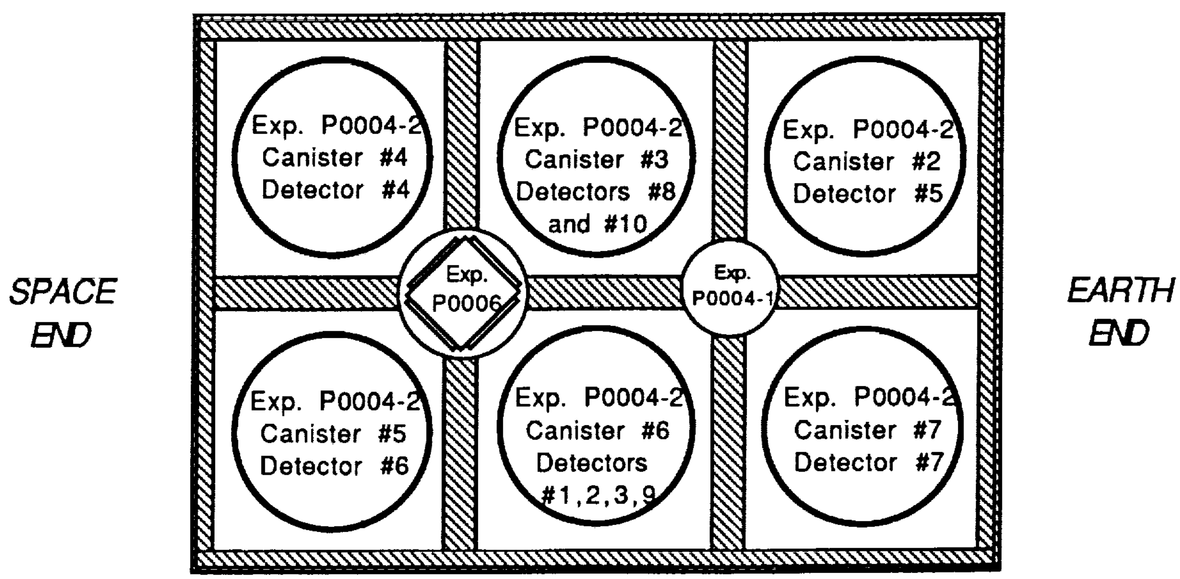


Fig. 2-3. Layout of canisters in LDEF Tray F2, photograph of actual tray and model layout.

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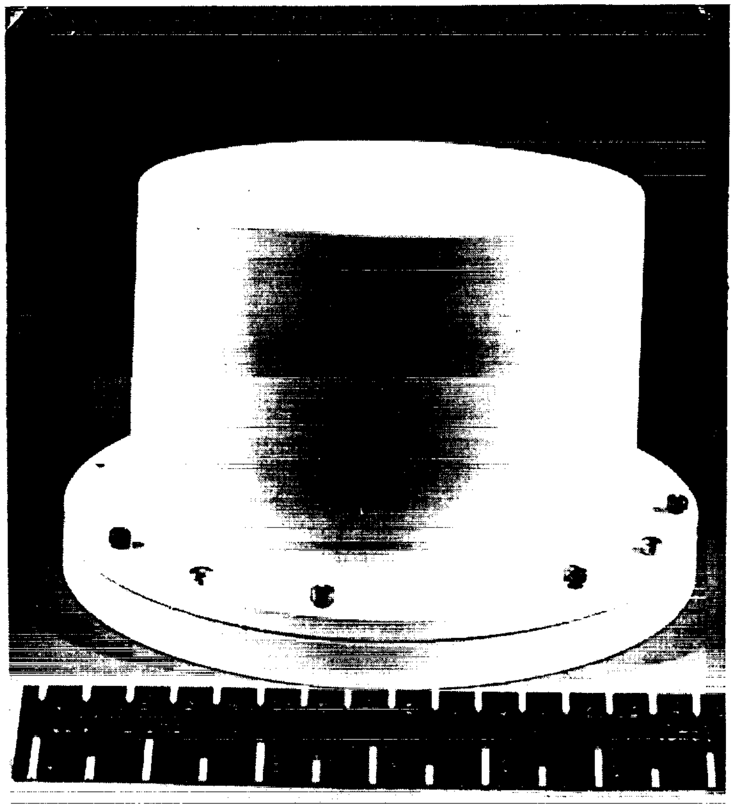

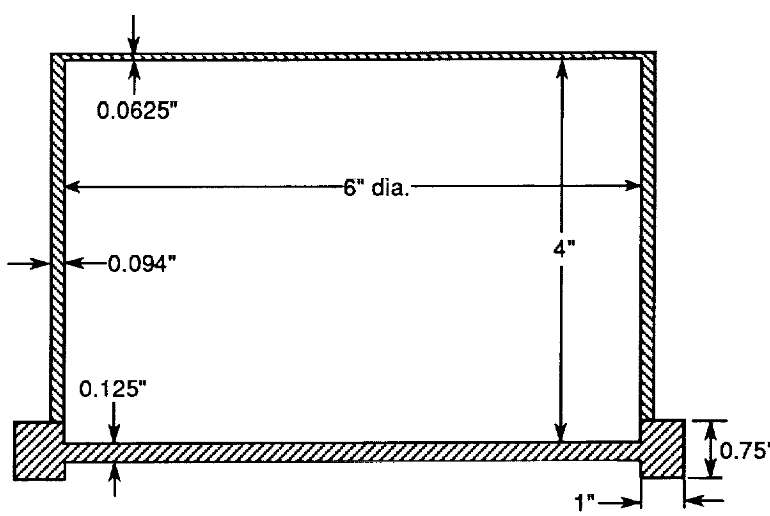

Fig. 2-4. Experiment P0006 canister, photograph of actual canister and model.

similarly but with a height of 2.75 inches and diameter of 4.0 inches. The P0004-2 canisters actually have a curved top, but this was simplified as a flat top for the model (Fig. 2-5). All of the canisters are made of aluminum.

2.3 Model of Experiment P0004 Dosimeters

Ten dosimetry packets were flown in the six P0004 SEED canisters. Materials properties assumed in modeling the P0004 (and P0006) dosimeters are summarized in Table 2-1, and dimensions and materials used in modeling the thermal cover and P0004 dosimetry packet are given in Figs. 2-6 and 2-7.

The locations of the dosimeters in the canisters is shown in Table. 2-2. The weight variation of individual seed bags[17] was small, so we have used an average seed density of 0.66 g/cm^3 for all canisters. The minimum TLD shielding (i.e., in the vertical direction, perpendicular to the plane of the tray) in terms of aluminum equivalent areal density is estimated here (bottom part of Table 2-2) to be 0.49, 6.1, and 11.0 g/cm^2 for TLDs placed at the top, middle, and bottom of the seeds, which is in agreement with the values of 0.48, 6.1, and 11.1 g/cm^2 determined by Benton, et al.[2] The actual location of the TLDs in the middle of canister #6 was uncertain, with Benton, et al. estimating a total depth of ~ 5 g/cm^2; here we have assumed these TLDs have the same depth (6.1 g/cm^2) as those located in the middle of the other canisters.

2.4 Model of Experiment P0006 Dosimeters

The P0006 dosimeter is made up of a stack of nine detector modules (the "main stack") with four additional modules attached to the sides of the main stack (Fig. 2-8). The main stack contains: (a) five sets of TLDs at various depths in the stack; (b) sheets of different types of PNTDs (CR-39, Millinex, Tuffak, and Sheffield); (c) a layer of CR-39 and silicon wafers for measuring LET spectra from silicon recoils; (d) a "neutron plate" containing ^{6}LiF foils, with and without Gd covers, for measuring low-energy neutrons; (e) a "fission foil plate" containing

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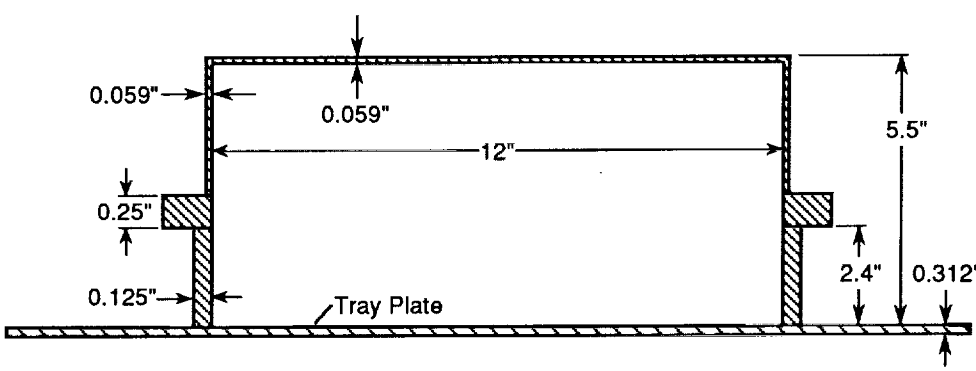
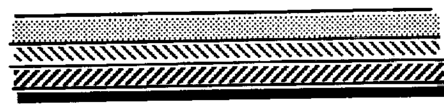


Fig. 2-5. SEEDS canister containing P0004 dosimeters, photographs of actual canister and model.

Table 2-1. Assumed material parameters for Exps. P0004 and P0006.

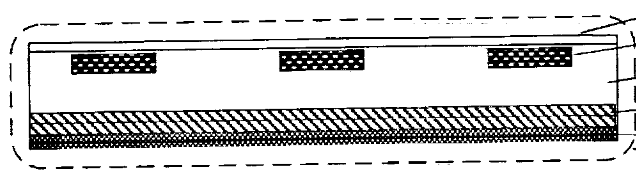
Component	Material	Atomic Composition	Density (g/cm**2)	100-MeV Proton Range (g/cm**2)	Relative Range
Detector Canisters	aluminum	Al	2.700	9.905	1.000
Tomato Seeds	cellulose	C20 H32 O5	0.660	7.703	0.778
TLD Holder	acrylic	C16 H14 O3	1.217	8.035	0.811
TLD-200		Ca F2	2.600	9.654	0.975
TLD-700		Li F	2.600	9.654	0.975
PNTD	CR-39	C12 H18 O7	1.296	7.800	0.787
PNTD	Melinex	C5 H4 O2	1.270	8.243	0.832
PNTD	Tuffak	C16 H14 O3	1.217	8.035	0.811
PNTD	Sheffield	C12 H14 O3	1.206	8.000	0.808
PNTD	Mica (Muscovite)	K Al3 Si3 O14 H2	2.800	9.366	0.946
Activation Sample	nickel	Ni	8.900	11.107	1.121
Activation Sample	vanadium	V	6.110	11.260	1.137
Activation Sample	tantalum	Ta	16.600	15.500	1.565
Activation Sample	indium	In	7.310	13.514	1.364
Thermal Shield	(composite)		1.640	8.885	0.897

Fig. 2-6. Exp. P0004 thermal shield.



Material	Thickness	units	Thickness (cm)	Density (g/cm**3)	Thickness (g/cm**2)	Proton Range at 100 MeV (g/cm**2)	Al Equiv. Thickness (g/cm**2)	Al. Equiv. Density (g/cm**3)
Teflon	5	mils	1.27E-02	1.98	0.025146	9.39	2.65E-02	2.09
silver	1600	angstroms	1.60E-05	10.50	0.000168	13.17	1.26E-04	7.90
steel	400	angstroms	4.00E-06	7.75	0.000031	11.26	2.73E-05	6.82
paint	4	mils	1.02E-02	1.20	0.012192	8.00	1.51E-02	1.49
		TOTAL:	0.0229		0.0375		0.0418	

Fig. 2-7. Exp. P0004 detector packet.



Component	Material	Thickness (cm)	Density (g/cm**3)	Thickness (g/cm**2)	Proton Range at 100 MeV (g/cm**2)	Al Equiv. Thickness (g/cm**2)	Al. Equiv. Density (g/cm**2)
Cover Sheet	Lexan	0.025	1.22	0.030	8.03	0.038	1.50
TLDHolder	acrylic	0.570	1.20	0.684	7.85	0.863	1.51
Plastic Det.	CR-39 sheets (2)	0.200	1.30	0.259	7.80	0.329	1.65
Plastic Det.	Tuffak sheets (2)	0.050	1.22	0.061	8.03	0.075	1.50
Pouch	polyethylene (2)	0.030	1.20	0.036	7.16	0.050	1.66
	TOTAL:	0.875		1.070		1.355	

Table 2-2. Detector locations in Experiment P0004.

	Seed Canister #2	***Seed Canister #3***	***Seed Canister #4***	***Seed Canister #5***	***Seed Canister #6***	***Seed Canister #7***
No. Detectors	1	2	1	1	4	1
Detector IDs	#5	#8,#10	#4	#6	#1,#2,#3,#9	#7
Seed Weights:						
seed bag A wt (lbs)	3.174	3.174	3.174	3.174	(distrbution	3.174
seed bag B wt (lbs)	3.174	3.174	3.174	3.174	uncertain)	3.174
seed bag C wt (lbs)	3.253	3.253	3.253	3.253		3.440
seed bag D wt (lbs)	3.440	3.440	3.440	3.440		3.440
TOTAL(LBS):	13.041	13.041	13.041	13.041	12.340	13.228
Seed Density:						
canister vol (cm**3)	9411	9411	9411	9411	9411	9411
detector vol (cm**3)	13.65	27.3	13.65	13.65	54.6	13.65
seed vol (cm**3)	9397	9384	9397	9397	9356	9397
seed mass (g)	5915	5915	5915	5915	5597	6000
seed den (g/cm**3)	0.63	0.63	0.63	0.63	0.60	0.64
canister inside height:	5.428	inches		canister lid thickness:	0.0558	inches
canister inside radius	6.000	inches		average seed density used:	0.66	g/cm**2

Distance from Top of Canisters to TLDs:

Detector Position	Layer	Layer Thickness (cm)	Cumulative Thickness (cm)	Layer Thickness (g/cm**2)	Cumulative Thickness (g/cm**2)	Cum. Al Equiv. (g/cm**2)
Top of Canister	Canister Lid	0.142	0.142	0.387	0.387	0.387
	Cover+Pouch	0.040	0.182	0.049	0.436	0.450
Middle of Canister	Canister Lid	0.142	0.142	0.387	0.387	0.387
	Seeds	6.710	6.852	4.395	4.782	6.039
	Cover+Pouch	0.040	6.892	0.049	4.831	6.102
Bottom of Canister	Canister Lid	0.142	0.142	0.387	0.387	0.387
	Seeds	12.912	13.054	8.457	8.844	10.876
	Cover+Pouch	0.040	13.094	0.049	8.893	10.939

Minimum ("Vertical") TLD Shielding:

Note-
Includes thermal
cover thickness of:
0.0229 cm
0.0375 g/cm**2
0.0418 g/cm**2 Al Eqv.

Detector No.	Canister No.	Detector Location in Canister	TLD Shielding (g/cm**2)	TLD Shielding (g/cm**2 Al Equiv.)
1	6	top	0.47	0.49
3,9	6	middle	4.87	6.1
2	6	bottom	8.93	11.0
4	4	middle	4.87	6.1
5	2	middle	4.87	6.1
6	5	middle	4.87	6.1
7	7	middle	4.87	6.1
8,10	3	middle	4.87	6.1

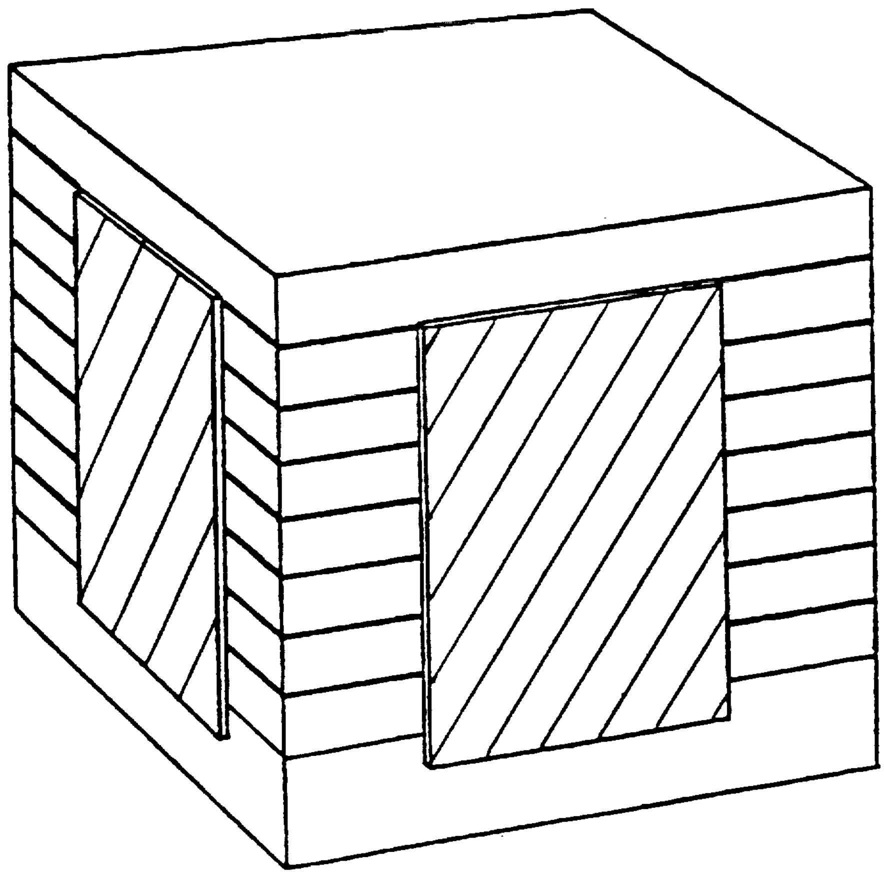


Fig. 2-8. Detector configuration for LDEF Exp. P0006, from Ref. 14. The main detector stack consists of nine modules, 4.5" square and 4.0" high. The four side modules are each 3.0" wide and 3.75" high.

^{181}Ta, ^{209}Bi, ^{232}Th, and ^{238}U foils, (f) an "activation plate" of V, Ni, Ta and In samples for measuring induced radioactivity, and (g) plates of aluminum dispersed throughout the stack. The side modules contain only PNTD materials. A materials list with dimensions is shown in Table 2-3, and the arrangement of materials is shown in Table 2-4.

In modeling the P0006 dosimeter, some of the 57 different material layers and 244 distinct material sheets listed in Table 2-4 for the main stack were combined. The sheets of PNTD materials and the TLD holder with TLDs were combined for each region between the aluminum plates to form a "model plastic" region. Layers 50 through 56 in Table 2-4 containing CR-39 and silicon wafers were combined as a separate region, and the neutron, activation, and fission plate regions were retained as separate layers. These simplifications result in a modeled main stack of 19 regions and one region each for the four side modules (Table 2-5). Average properties were used for the neutron and fission plate regions. The four activation samples were modeled separately as four different regions within the layer since the samples are relatively thick and vary substantially in terms of areal density. The com-geom model of the P0006 detector and canister is shown in Fig. 2-9.

2.5 Model of Tray with Contents

Figure 2-10 shows a view of the com-geom model of the F2 tray with Exps. P0004 and P0006 in place.

Table 2-3. Experiment P0006 materials and dimensions.

Component	Material	Dimensions
TLD Holder Plate	Lexan	4.25 in. x 4.25 in. x 1.5 mm thick
TLDs	LiF, CaF_2	0.25 in. x 0.25 in. x 0.035 in. thick
PNTD	CR-39	4.25 in. x 4.25 in. x 1000 μm thick (typ.)
PNTD	Melinex	4.25 in. x 4.25 in. x 250 μm thick
PNTD	Tuffack	4.25 in. x 4.25 in. x 250 μm thick
PNTD	Sheffield	4.25 in. x 4.25 in. x 250 μm thick
Neutron Foil Holder Plate	acrylic	4.25 in. x 4.25 in. x 0.125 in. thick
Neutron Foil	6LiF	0.625 in. dia. x 4.5 mg/cm**2 thick
Neutron Foil Cover	Gd	0.625 in. dia. x 0.0025 in. thick
Fission Foil Holder Plate	Lexan	4.25 in. x 4.25 in. x 1.5 mm. thick
Fission Foil	Ta-181	0.75 in. dia. x 0.15 mm thick
Fission Foil	Bi-209	1.5 in. x 0.5 in. x 1.3 mm thick
Fission Foil	Th-232	0.5 in. dia. x 0.10 mm thick
Fission Foil	U-238	0.5 in. dia. x 0.025 mm thick
Fission Track Detector	Muscovite Mica	0.09 ± 0.04 mm thick
Activation Sample	V	2.0 in. x 2.0 in. x 0.25 in. thick
Activation Sample	Ni	2.0 in. x 2.0 in. x 0.25 in. thick
Activation Sample	Ta	2.0 in. x 2.0 in. x 0.25 in. thick
Activation Sample	In	2.0 in. x 2.0 in. x 0.25 in. thick
Silicon Wafer	Si	360 μm thick
Aluminum Plate	Al	4.25 in. x 4.25 in. x 0.0625 in. thick

Table 2-4. Material layers in Experiment P0006 dosimeter.

Stack	Exp. Module No.	Model Region No.	Layer No.	Material	No. Sheets / Layer	Sheet Thickness (cm)	Layer Thickness (cm)	Layer Thickness (g/cm**2)	Cum. Thickness (cm)	Cum. Thickness (g/cm**2)	AE Layer Thickness (g/cm**2)	AE Cum. Thickness (g/cm**2)	AE Thick. incl Lid & Cover (g/cm**2)
Main	1	1	1	TLD Plate #1	1	0.159	0.159	0.206	0.159	0.206	0.261	0.261	0.74
Main	1	1	2	CR-39	2	0.100	0.200	0.259	0.359	0.466	0.329	0.590	1.06
Main	1	1	3	Melinex	8	0.025	0.200	0.254	0.559	0.720	0.305	0.895	1.37
Main	1	1	4	Tuffak	8	0.025	0.200	0.243	0.759	0.963	0.300	1.195	1.67
Main	1	1	5	Sheffield	14	0.025	0.350	0.422	1.109	1.385	0.520	1.715	2.19
Main	1	1	6	Mica	2	0.008	0.016	0.045	1.125	1.430	0.055	1.771	2.25
Main	2	2	7	Al Plate	1	0.157	0.157	0.428	1.282	1.858	0.428	2.199	2.67
Main	2	3	8	CR-39	2	0.100	0.200	0.259	1.482	2.117	0.329	2.528	3.00
Main	2	3	9	Melinex	8	0.025	0.200	0.254	1.682	2.371	0.305	2.833	3.31
Main	2	3	10	Tuffak	8	0.025	0.200	0.243	1.882	2.615	0.300	3.133	3.61
Main	2	3	11	Sheffield	10	0.025	0.250	0.302	2.132	2.916	0.372	3.505	3.98
Main	2	3	12	TLD Plate #2	1	0.159	0.159	0.206	2.290	3.122	0.261	3.765	4.24
Main	3	4	13	Al Plate	1	0.157	0.157	0.428	2.447	3.550	0.428	4.193	4.67
Main	3	5	14	CR-39	2	0.100	0.200	0.259	2.647	3.810	0.329	4.522	5.00
Main	3	5	15	Melinex	8	0.025	0.200	0.254	2.847	4.064	0.305	4.828	5.30
Main	3	5	16	Tuffak	8	0.025	0.200	0.243	3.047	4.307	0.300	5.128	5.60
Main	3	5	17	Sheffield	10	0.025	0.250	0.302	3.297	4.609	0.372	5.499	5.97
Main	4	6	18	Al Plate	1	0.157	0.157	0.428	3.454	5.037	0.428	5.928	6.40
Main	4	7	19	CR-39	2	0.100	0.200	0.259	3.654	5.296	0.329	6.257	6.73
Main	4	7	20	Melinex	8	0.025	0.200	0.254	3.854	5.550	0.305	6.562	7.04
Main	4	7	21	Tuffak	8	0.025	0.200	0.243	4.054	5.793	0.300	6.862	7.34
Main	4	7	22	Sheffield	10	0.025	0.250	0.302	4.304	6.095	0.372	7.234	7.71
Main	5	8	23	Al Plate	1	0.157	0.157	0.428	4.461	6.523	0.428	7.662	8.14
Main	5	9	24	TLD Plate #3	1	0.159	0.159	0.206	4.619	6.729	0.261	7.922	8.40
Main	5	9	25	CR-39	2	0.100	0.200	0.259	4.819	6.988	0.329	8.251	8.73
Main	5	9	26	Melinex	8	0.025	0.200	0.254	5.019	7.242	0.305	8.557	9.03
Main	5	9	27	Tuffak	8	0.025	0.200	0.243	5.219	7.486	0.300	8.857	9.33
Main	5	9	28	Sheffield	10	0.025	0.250	0.302	5.469	7.787	0.372	9.228	9.70
Main	6	10	29	Al Plate	1	0.157	0.157	0.428	5.626	8.215	0.428	9.656	10.13
Main	6	11	30	CR-39	2	0.100	0.200	0.259	5.826	8.475	0.329	9.986	10.46
Main	6	11	31	Melinex	8	0.025	0.200	0.254	6.026	8.729	0.305	10.291	10.77
Main	6	11	32	Tuffak	8	0.025	0.200	0.243	6.226	8.972	0.300	10.591	11.07
Main	6	11	33	Sheffield	10	0.025	0.250	0.302	6.476	9.273	0.372	10.963	11.44
Main	7	12	34	Al Plate	1	0.157	0.157	0.428	6.633	9.702	0.428	11.391	11.87
Main	7	13	35	TLD Plate #4	1	0.159	0.159	0.206	6.792	9.908	0.261	11.651	12.13
Main	7	13	36	CR-39	2	0.100	0.200	0.259	6.992	10.167	0.329	11.980	12.46
Main	7	13	37	Melinex	8	0.025	0.200	0.254	7.192	10.421	0.305	12.286	12.76
Main	7	13	38	Tuffak	8	0.025	0.200	0.243	7.392	10.664	0.300	12.586	13.06
Main	7	13	39	Sheffield	10	0.025	0.250	0.302	7.642	10.966	0.372	12.957	13.43
Main	8	14	40	Al Plate	1	0.157	0.157	0.428	7.799	11.394	0.428	13.385	13.86
Main	8	15	41	CR-39	2	0.100	0.200	0.259	7.999	11.653	0.329	13.714	14.19
Main	8	15	42	Melinex	4	0.025	0.100	0.127	8.099	11.780	0.153	13.867	14.34
Main	8	15	43	Tuffak	4	0.025	0.100	0.122	8.199	11.902	0.150	14.017	14.49
Main	8	15	44	Sheffield	2	0.025	0.050	0.060	8.249	11.962	0.074	14.091	14.57
Main	8	15	45	Mica	2	0.008	0.016	0.045	8.265	12.007	0.055	14.147	14.62
Main	8	15	46	Melinex	2	0.025	0.050	0.064	8.315	12.071	0.076	14.223	14.70
Main	8	15	47	Tuffak	2	0.025	0.050	0.061	8.365	12.131	0.075	14.298	14.77
Main	8	15	48	Sheffield	4	0.025	0.100	0.121	8.465	12.252	0.149	14.447	14.92
Main	9	15	49	TLD Plate #5	1	0.159	0.159	0.206	8.623	12.458	0.261	14.707	15.18
Main	9	16	50	CR-39	1	0.075	0.075	0.097	8.698	12.556	0.123	14.831	15.31
Main	9	16	51	Silicon	1	0.036	0.036	0.084	8.734	12.639	0.086	14.916	15.39
Main	9	16	52	CR-39	1	0.075	0.075	0.097	8.809	12.737	0.123	15.040	15.51
Main	9	16	53	Silicon	1	0.036	0.036	0.084	8.845	12.821	0.086	15.125	15.60
Main	9	16	54	CR-39	1	0.075	0.075	0.097	8.920	12.918	0.123	15.249	15.72
Main	9	17	55	Neutron Plate	1	0.318	0.318	0.413	9.238	13.330	0.521	15.770	16.25
Main	9	18	56	Activation Plate	1	0.635	0.635	6.179	9.873	19.509	3.823	19.593	20.07
Main	9	19	57	Fission Plate	1	0.159	0.159	0.176	10.032	19.685	0.223	19.815	20.29
Sides	.10-13	.20-23	1	CR-39	2	0.100	0.200	0.259	0.200	0.259	0.329	0.329	
			2	Melinex	2	0.025	0.050	0.064	0.250	0.323	0.076	0.405	
			3	Tuffak	2	0.025	0.050	0.061	0.300	0.384	0.075	0.480	
			4	Sheffield	2	0.025	0.050	0.060	0.350	0.444	0.074	0.555	

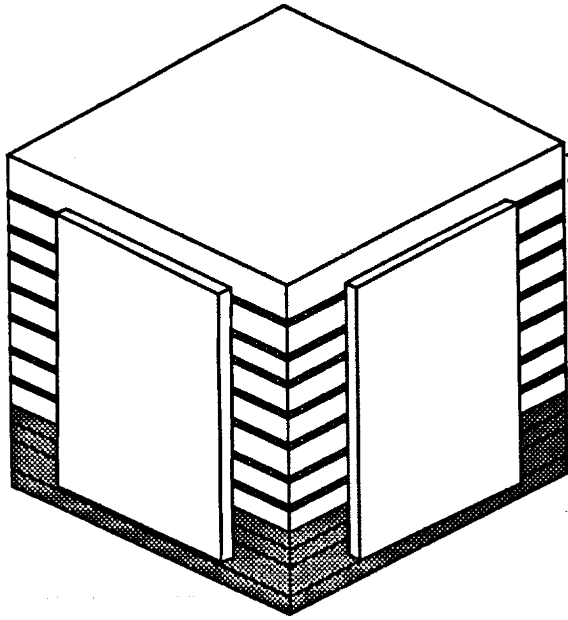


Table 2-5. Model of Exp. P0006 detector.

Stack	Model Region No.	Material	Region Thickness (cm)	Region Thickness (g/cm**2)	Average Density (g/cm**3)	Al Equiv. Density (g/cm**3)	Al Equiv. Thickness (g/cm**2)
Main	1	plastic	1.12	1.43	1.27	1.57	1.77
Main	2	Al	0.16	0.43	2.73	2.73	0.43
Main	3	plastic	1.01	1.26	1.25	1.55	1.57
Main	4	Al	0.16	0.43	2.73	2.73	0.43
Main	5	plastic	0.85	1.06	1.24	1.54	1.31
Main	6	Al	0.16	0.43	2.73	2.73	0.43
Main	7	plastic	0.85	1.06	1.24	1.54	1.31
Main	8	Al	0.16	0.43	2.73	2.73	0.43
Main	9	plastic	1.01	1.26	1.25	1.55	1.57
Main	10	Al	0.16	0.43	2.73	2.73	0.43
Main	11	plastic	0.85	1.06	1.24	1.54	1.31
Main	12	Al	0.16	0.43	2.73	2.73	0.43
Main	13	plastic	1.01	1.26	1.25	1.55	1.57
Main	14	Al	0.16	0.43	2.73	2.73	0.43
Main	15	plastic	0.82	1.06	1.29	1.60	1.32
Main	16	Si/CR-39	0.3	0.46	1.55	1.82	0.54
Main	17	Neutron Plate	0.32	0.41	1.30	1.64	0.52
Main	18	Activation Plate	0.64	6.18(av)	9.73(av)	6.02(av)	3.82(av)
Main	19	Fission Plate	0.16	0.18	1.11	1.40	0.22
			10.03	19.69			19.82
Sides	20,21,22,23	plastic	0.35	0.44	1.27	1.59	0.56

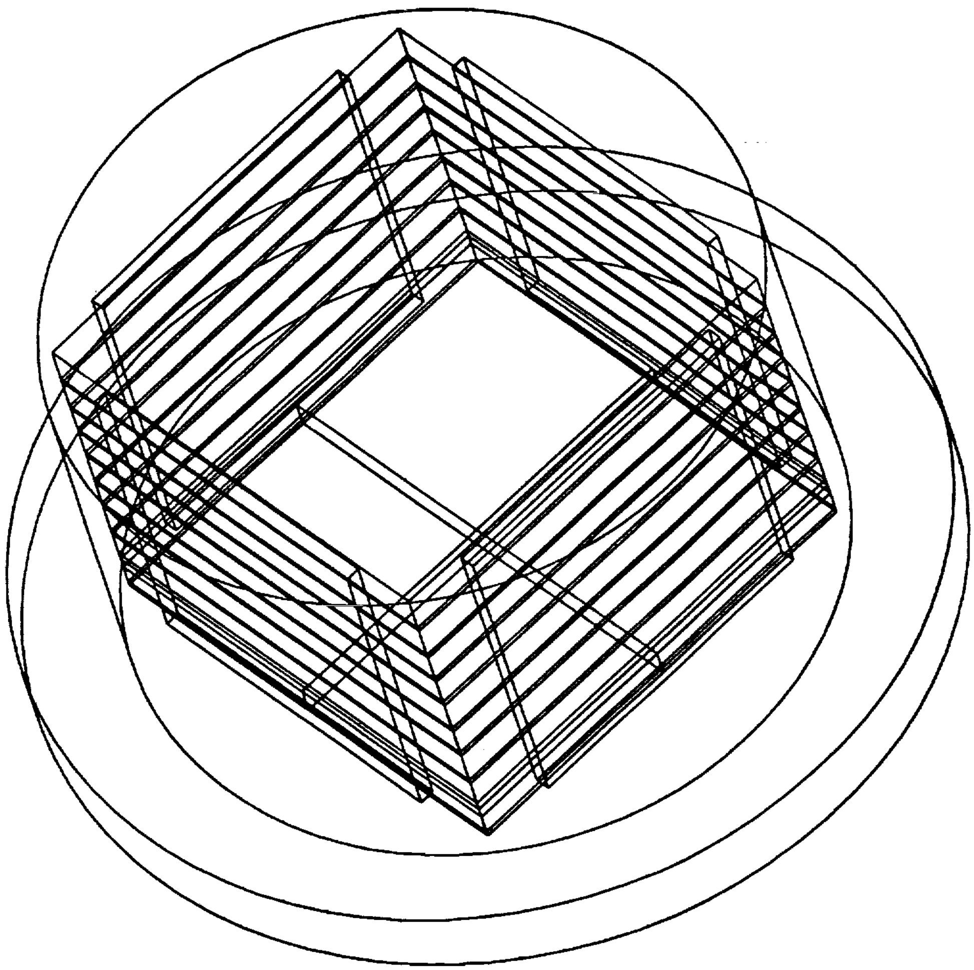


Fig. 2-9. Geometry model of P0006 and canister.

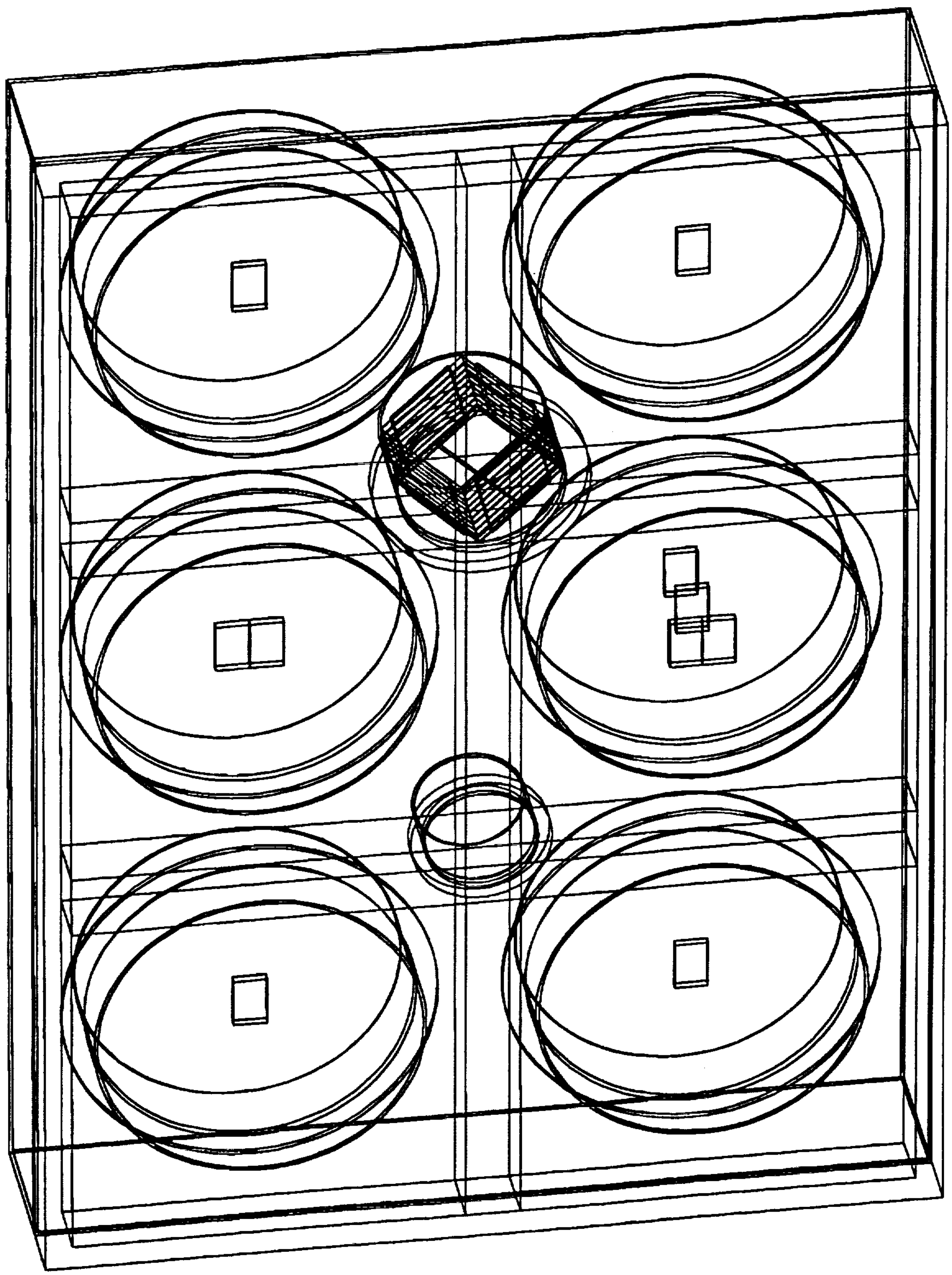


Fig. 2-10. Geometry model of LDEF Tray F2 with Exp. P0004 and P0006 detectors.

3. Modeling of Dosimetry Experiment M0004

Experiment M0004 on space environment effects on fiber optics[22] was located in Tray F8 near the LDEF leading edge. The tray contained two dosimetry packets in each of two canisters, with each packet containing both TLDs and PNTDs.

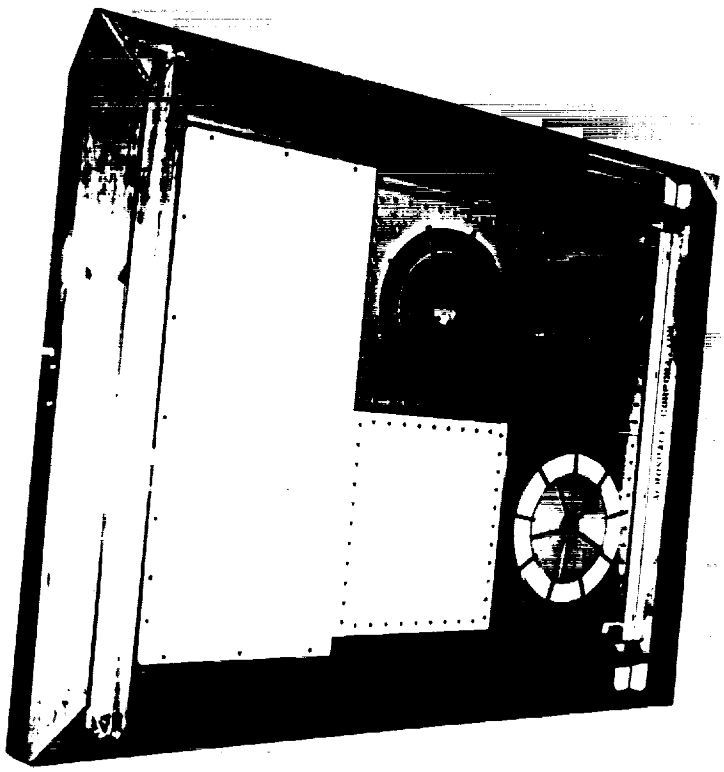
3.1 Modeling of Tray and Contents

The F8 tray is the same as the 6-inch deep F2 tray described previously for Exps. P0004 and P0006. The layout of components in the tray is indicated in Fig. 3-1. The main components are four fiber optics packages, a magnetic tape module (MTM), an experiment power and data system (EPDS) unit, batteries, and two detector canisters. The canisters are inclined relative to the plane parallel to the tray bottom as indicated in Fig. 3-2. In the modeling, the axes of the cylindrical canisters were assumed to be tilted+30° and -30° relative to the normal of the tray mounting plate.

The tray contains ten batteries, with two located under each of the one-sixth tray sections for the detector section and the four sections containing the fiber bundles.

Weights for the MTM, EPDS, and tray were obtained from Ref. 11, weights for the batteries were provided by the LDEF Project Science Office[9], and the weight of the canisters and dosimeters were determined from the information given in Ref. 15. Estimates of the weights for other components were estimated to obtain agreement with the known total tray weight (Ref. 10) as shown in Table. 3-1. Estimates of aluminum equivalent densities for M0004 materials are given in Table 3-2.

Experiment M0004 materials and aluminum equivalent densities used in the modeling are listed in Table. 3-3.



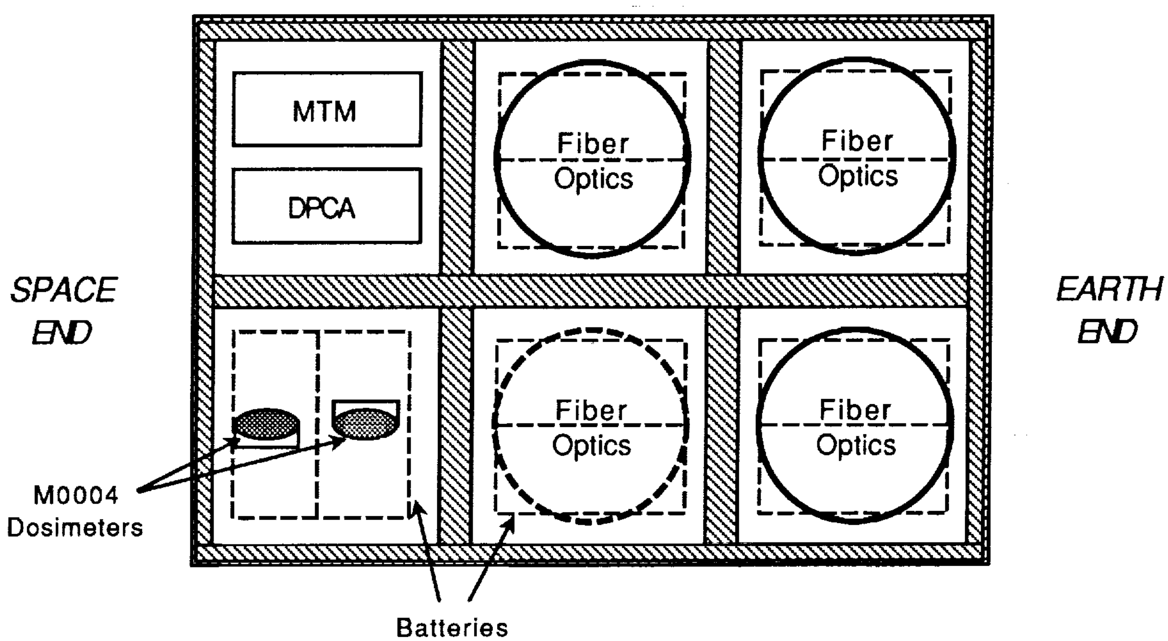


Fig. 3-1. Layout of LDEF Tray F8 containing Exp. M0004 dosimeters, photograpy of tray (with thermal covers) and model layout.

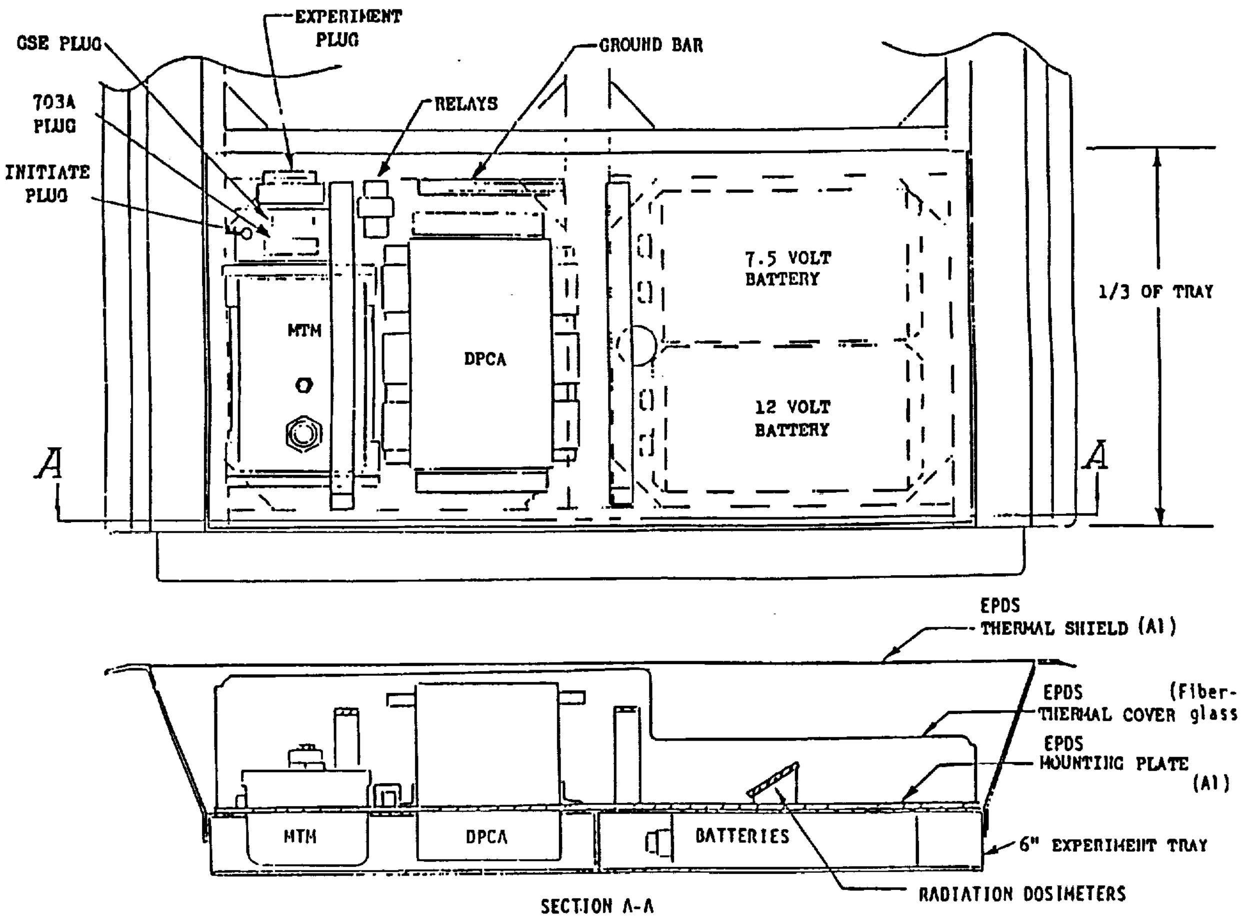


Fig. 3-2. Layout of components in the one-third section of Tray F8 containing the Exp. M0004 radiation dosimeters, from Ref. 15.

Table 3-1. Weight allocation for model of LDEF Tray F8.

Component	No.	Width (in.)	Height (in.)	Depth (in.)	Volume (in**3)	Volume (cm**3)	Assumed Av. Density (g/cm**3)	Weight (lbs)
Tray	1						2.7	39.0
Batteries	10	10.5	2.5	6.50	1,706	27960	1.4	87.0
DPCA	1	8.0	7.5	13.00	780	12782	1.0	28.2
MPM	1	5.0	6.5	13.00	423	6924	1.0	15.0
Mounting Plates-bottom	5	16.0	16.0	0.19	48	787	2.7	23.4
Thermal covers	3	16.0	16.0	0.12	30	499	2.0	6.6
Fiber Optics Packages	4	radius=	6.0	height=	2	3707	1.7	55.6
Mounting Plates - top	3					1317	2.7	7.8
EPDS Shield & Cover	1	16.0	16.0	0.04	10	67	2.5	0.4
M0004 Canister	2							0.1
M00004 Detectors	2							0.1
						Total Tray Weight(lbs):		263.1

Table 3-2. Aluminum equivalence for Exp. M0004 materials.

Component	Assumed Material	Average Density (g/cm**3)	Proton Range @ 100 MeV (g/cm**2)	Al. Equiv. Density (g/cm**3)
Tray	aluminum	2.73	9.90	2.73
Batteries	copper	1.40	11.47	1.21
DPCA	copper	1.00	11.47	0.86
MPM	copper	1.00	11.47	0.86
Mounting Plates-bottom	aluminum	2.73	9.90	2.73
Thermal covers	composite	2.00	8.77	2.26
Fiber Optics Packages	glass	1.70	9.24	1.82
Mounting Plates - top	aluminum	2.73	9.90	2.73
EPDS Shield & Cover	composite	2.00	8.77	2.26
M0004 Canister	aluminum	2.73	9.90	2.73
M00004 Detector	plastic	1.27	8.02	1.57

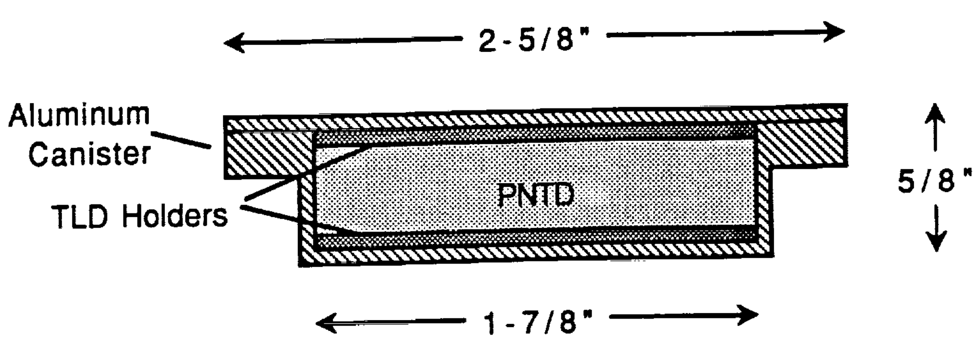


Fig. 3-3. Experiment M0004 detector canister model.

3.2 Experiment M0004 Detector Model

The aluminum detector canisters were cylindrical and modeled as shown in Fig. 3-3, with the dimensions from Ref. 15.

Table 3-2 Part (a) shows materials and thicknesses for the thermal cover and detector. The detector contained two sets of TLDs with PNTD materials in between. The TLD depths are 1.25 and 2.50 g/cm^2, or 1.37 and 2.92 g/cm^2 aluminum equivalent based on 100-MeV proton ranges. The detector was modeled as a single region of "plastic" having the average density shown in Table 3-2 Part (b).

3.3 Com-Geom Model

The combinatorial geometry model of the bodies comprising Tray F8 and its contents is shown in Fig. 3-4.

Table 3-3. Modeling of M0004 detector.

(a) M0004 detector - as flown.

Layer No.	Component	Material	Sheets per Layer	Thickness per Sheet	units	Layer Thickness (cm)	Cumulative Depth to Layer Top (cm)	Density (g/cm**3)	Layer Thickness (g/cm**2)	Cumulative Depth to Layer Top (g/cm**2)	Proton Range @ 100 MeV (g/cm**2)	Al. Equiv. Layer Thick. (g/cm**2)	Al. Equiv. Cum. Thickness (g/cm**2)
1	Thermal Shield	aluminum	1	0.04	inches	0.10		2.70	0.27		9.90	0.27	
2	Thermal Cover	fiberglass	1	0.12	inches	0.30	0.10	1.71	0.52	0.27	8.00	0.64	0.27
3	Al Tape	aluminum	1	0.0028	inches	0.01	0.41	2.70	0.02	0.79	9.90	0.02	0.92
4	Tape	plastic	1	0.0016	inches	0.00	0.41	0.98	0.00	0.81	8.00	0.00	0.94
5	Canister Lid	aluminum	1	0.0625	inches	0.16	0.42	2.70	0.43	0.82	9.90	0.43	0.94
6	TLDs	LiF,CaF2		0.013451	(av) in.	0.03	0.58	1.20	0.04	1.25	9.60	0.04	1.37
7	TLD Holder #1	acrylic	1	0.04483	(av) in.	0.11	0.61	1.20	0.14	1.29	7.85	0.17	1.41
8	PNTD	CR-39	2	1000	μm	0.20	0.72	1.30	0.26	1.42	7.80	0.33	1.59
9	PNTD	Sheffield	4	250	μm	0.10	0.92	1.21	0.12	1.68	8.00	0.15	1.91
10	PNTD	Melinex	4	250	μm	0.10	1.02	1.27	0.13	1.80	8.24	0.15	2.06
11	PNTD	Tuffack	4	250	μm	0.10	1.12	1.22	0.12	1.93	8.03	0.15	2.22
12	PNTD	CR-39	2	1000	μm	0.20	1.22	1.30	0.26	2.05	7.80	0.33	2.37
13	PNTD	Sheffield	2	250	μm	0.05	1.42	1.21	0.06	2.31	8.00	0.07	2.70
14	PNTD	Melinex	2	250	μm	0.05	1.47	1.27	0.06	2.37	8.24	0.08	2.77
15	PNTD	Tuffack	2	250	μm	0.05	1.52	1.22	0.06	2.44	8.03	0.08	2.85
16	TLDs	LiF,CaF2		0.013451	(av) in.	0.03	1.57	1.20	0.04	2.50	9.60	0.04	2.92
17	TLD Holder #2	acrylic	1	0.04483	(av) in.	0.11	1.61	1.20	0.14	2.54	7.85	0.17	2.96
					TOTAL:	1.72	1.72			2.67			3.14

(b) M0004 detector - as modeled.

Layer No.	Material	Thickness (cm)	Average Density (g/cm**3)	Thickness (g/cm**2)	Al. Equiv. Thickness (g/cm**2)	Al. Equiv. Density (g/cm**3)
1	Thermal Blanket	0.418	1.958	0.818	0.942	2.257
2	Canister Lid	0.159	2.700	0.429	0.429	2.700
3	"Plastic"	1.146	1.246	1.428	1.766	1.541
	TOTAL:	1.72		2.67	3.14	

- Distance from top of canister to TLD set #1 = 0.176 cm.
- Distance from top of canister to TLD set #2 = 1.17 cm.

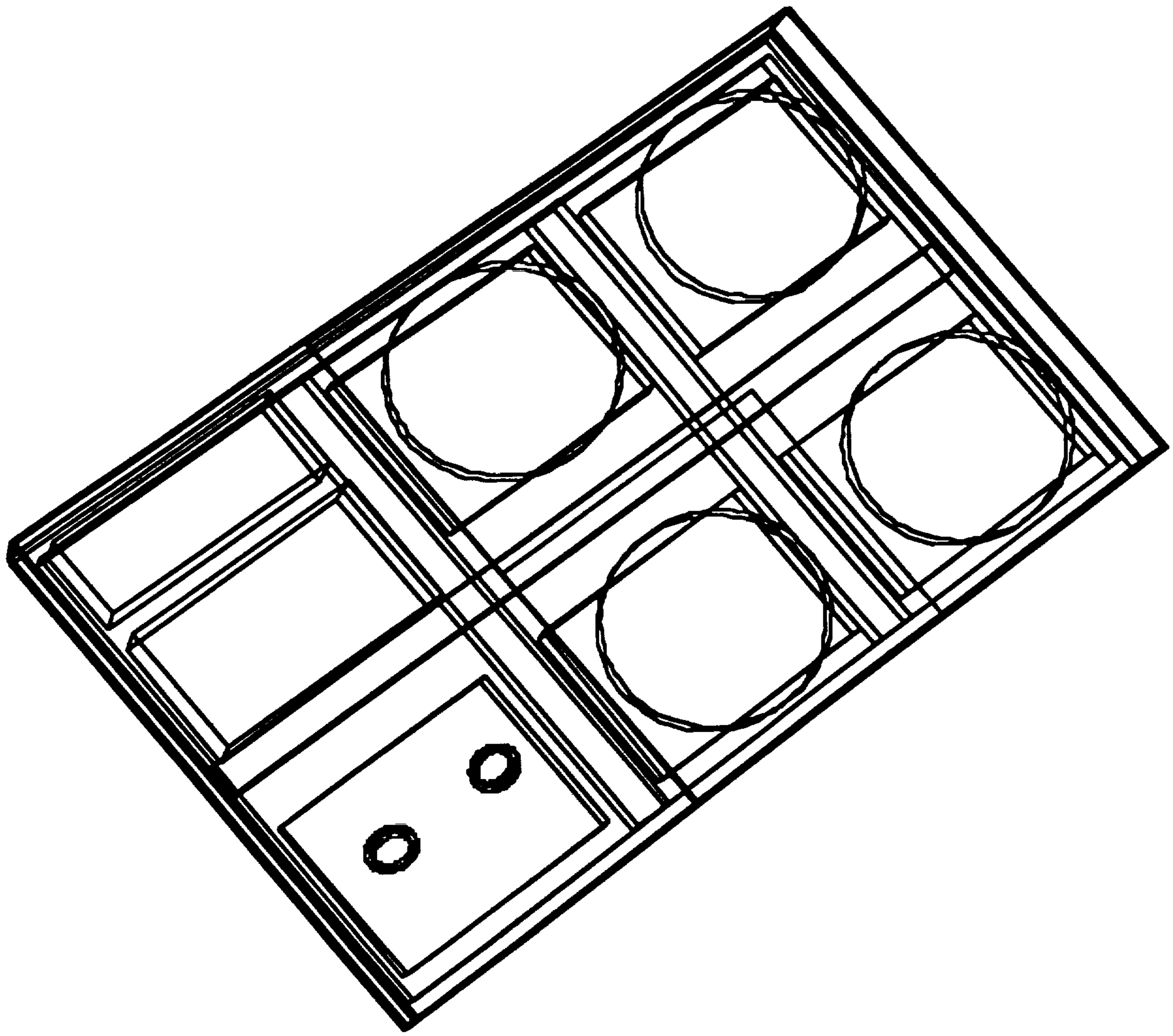


Fig. 3-4. Geometry model of LDEF Tray F8 with Exp. M0004 radiation detectors.

4. Modeling of Experiment M0001

The M0001 experiment to measure heavy ions in space is located in two trays (H3 and H12) on the space end of LDEF[23]. Each tray contains four modules of CR-39 detector material, with each module inside a hollow aluminum coffer. The dimensions for each detector module and coffer are shown in Fig. 4-1. The center of each module coincides with the center of one quadrant of an LDEF end tray. In Tray H3 the shorter sides of the modules are parallel to the LDEF velocity vector, and in Tray H12 the longer sides are parallel to the velocity vector.

A view of the modeled Exp. M0001 tray and contents is shown in Fig. 4-2.

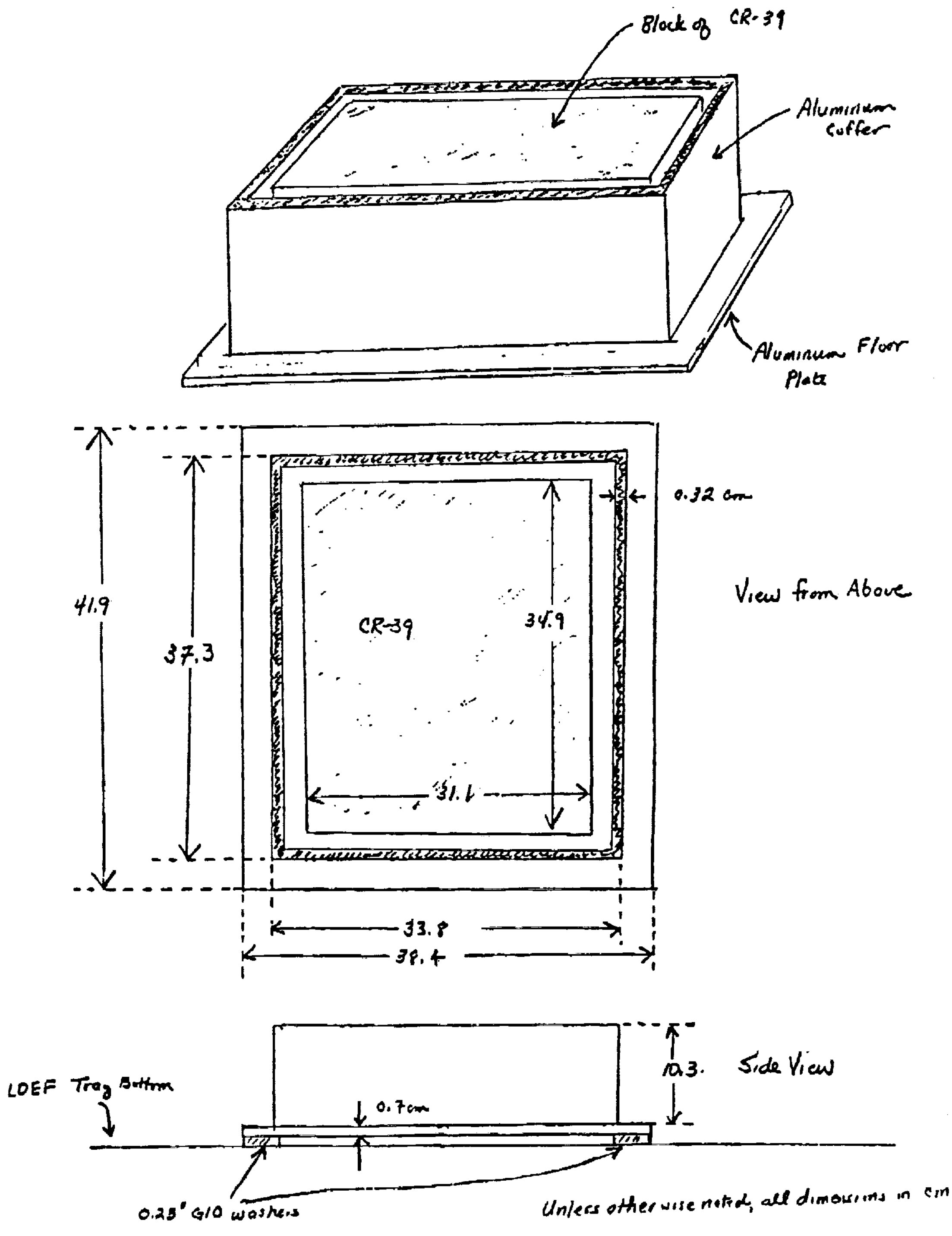


Fig. 4-1. Single module dimensions for Exp. M0001 detectors, from Ref. 18.

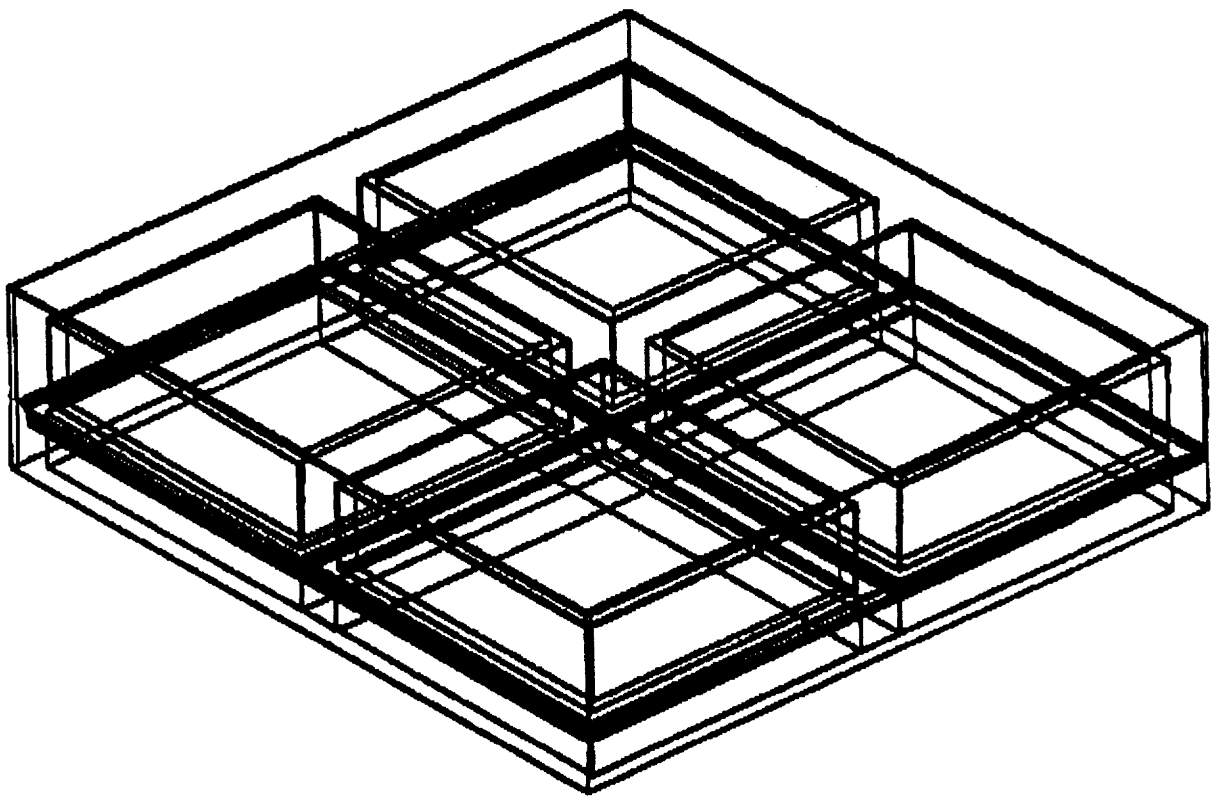


Fig. 4-2. Geometry model of Exp. M0001 detector modules and LDEF experiment tray.

5. Initial Applications

Some example results obtained in initial applications as part of verifying the operation of the LDEF geometry model computer program are given in this section. The geometry module has been used with a transport code and solid-angle sectoring methods to obtain preliminary absorbed dose estimates taking into account the 3-D shielding of LDEF (Sec. 5-1). As an example of applying the geometry model as a standalone computer program to determine shielding distributions, 3-D shielding distributions for several locations in the P0004 and P0006 detectors have been generated (Sec. 5-2). The geometry program has been provided to NRL where it is being used to evaluate shielding effects related to the analysis of Exp. M0001 data.

5.1 Preliminary Dose Estimates

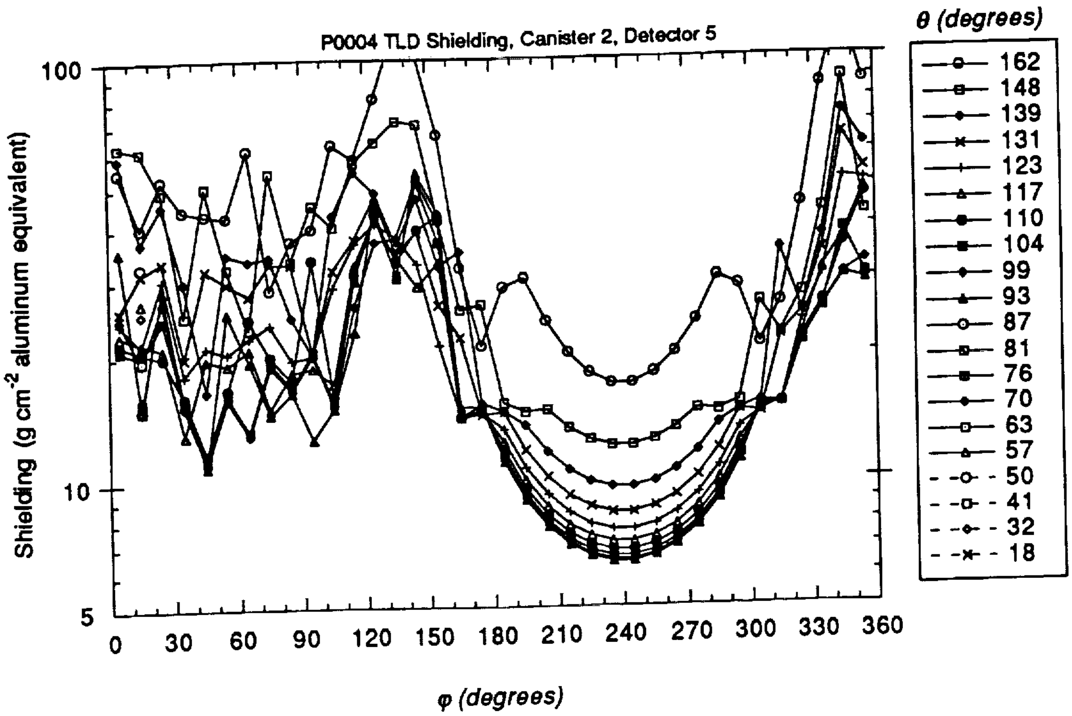
The LDEF geometry model has been used with proton transport calculations to obtain some initial estimates of the TLD absorbed dose measurements made in experiments P0004, P0006, and M0004 with 3-D shielding effects taken into account. Shielding distributions were generated around the dosimeters using a 3-D angular grid of 720 directions in equal solid angle increments. Proton transport calculations were made for the aluminum equivalent shielding thickness along each direction, representing a solid angle sector, with the TLD treated as a plane detector. The one-dimensional MSFC transport code of Burrell[24] was used with the anisotropic trapped proton flux at 450 km and solar minimum[25] as input.

For all of the TLD locations in Exps. P0004 and P0006, the predicted and measured dose agreement was within about 30%, but the predicted dose for Exp. M0004 was substantially higher than measured. These initial 3-D dose comparisons are very preliminary and should not be regarded as definitive comparisons with LDEF measurements. For example, the calculations here were made for trapped proton exposure at 450 km altitude and solar minimum conditions, whereas definitive estimates need to take into account the altitude and solar cycle variations during the LDEF mission (which is work in progress).

5.2 Example Shielding Distributions

Figure 5-1 shows example shielding variations for two TLD locations: for TLDs located in the middle of a seed canister in Exp. P0004 (minimum shielding thickness of 6.1 g/cm^2 aluminum equivalent), and for TLDs located at the bottom of the P0006 detector stack (minimum shielding thickness of 15.4 g/cm^2 aluminum equivalent). The shielding thicknesses are along rays generated using a spacecraft coordinate system where +z points toward zenith, +y is in the direction of the LDEF velocity vector (east), and the +x axis points south. Ray directions are defined by the polar angle θ, measured from +z, and the aximuthal angle φ, measured from +x toward +y. In this coordinate system the normal direction for the P0004 and P0006 canisters (corresponding to the direction perpendicular to the plane of the experiment tray and looking outward from the tray bottom toward space) is at $\theta = 90°$ and $\varphi = 240°$.

Figure 5-2 shows the shielding distribution in a horizontal plane around one of the PNTD side modules of Exp. P0006. Here a local coordinate system is used with the angle α measured in a plane parallel to the tray top. The origin is at the outer surface of the module on the middle of the module face. The "dips" in the shielding distribution designated as (a), (b), and (c) occur for directions between the seed canisters, with the large peak in the distribution (d) corresponding to directions going through lower trays (toward earth-end) and through the center ring of the spacecraft structure. The other P0006 side modules see a similar horizontal shielding distribution but displaced by 90°.



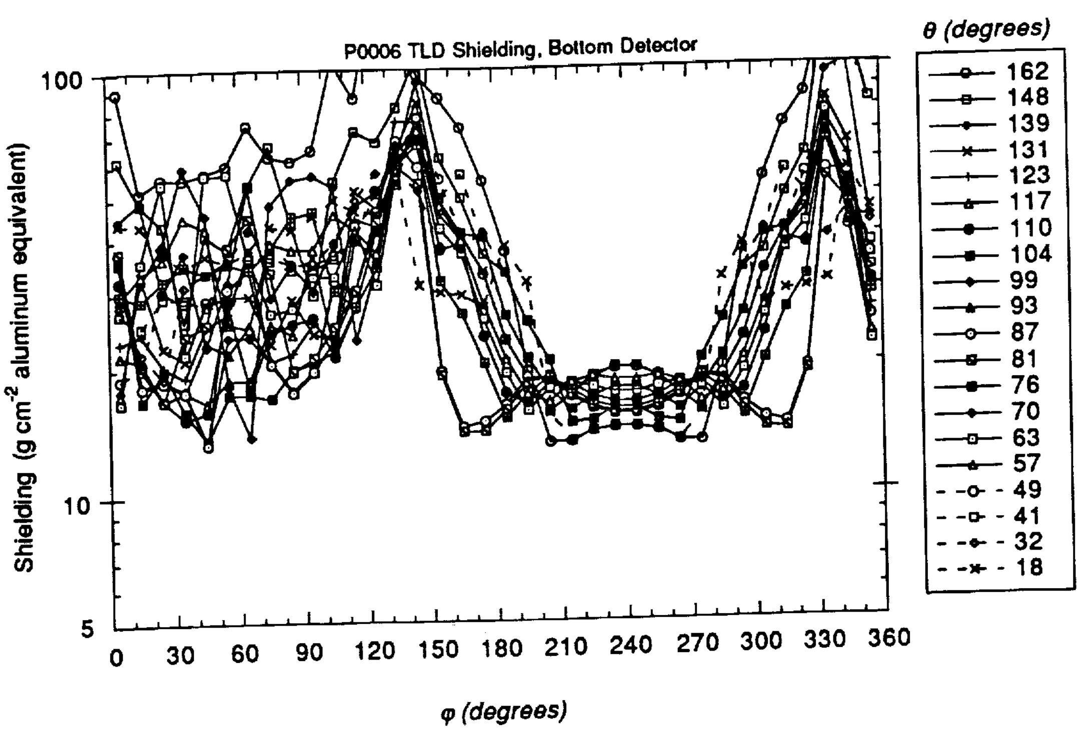


Fig. 5-1. Example shielding distributions for two TLD locations, one in Exp. P0004 (top) and one in Exp. P0006 (bottom).

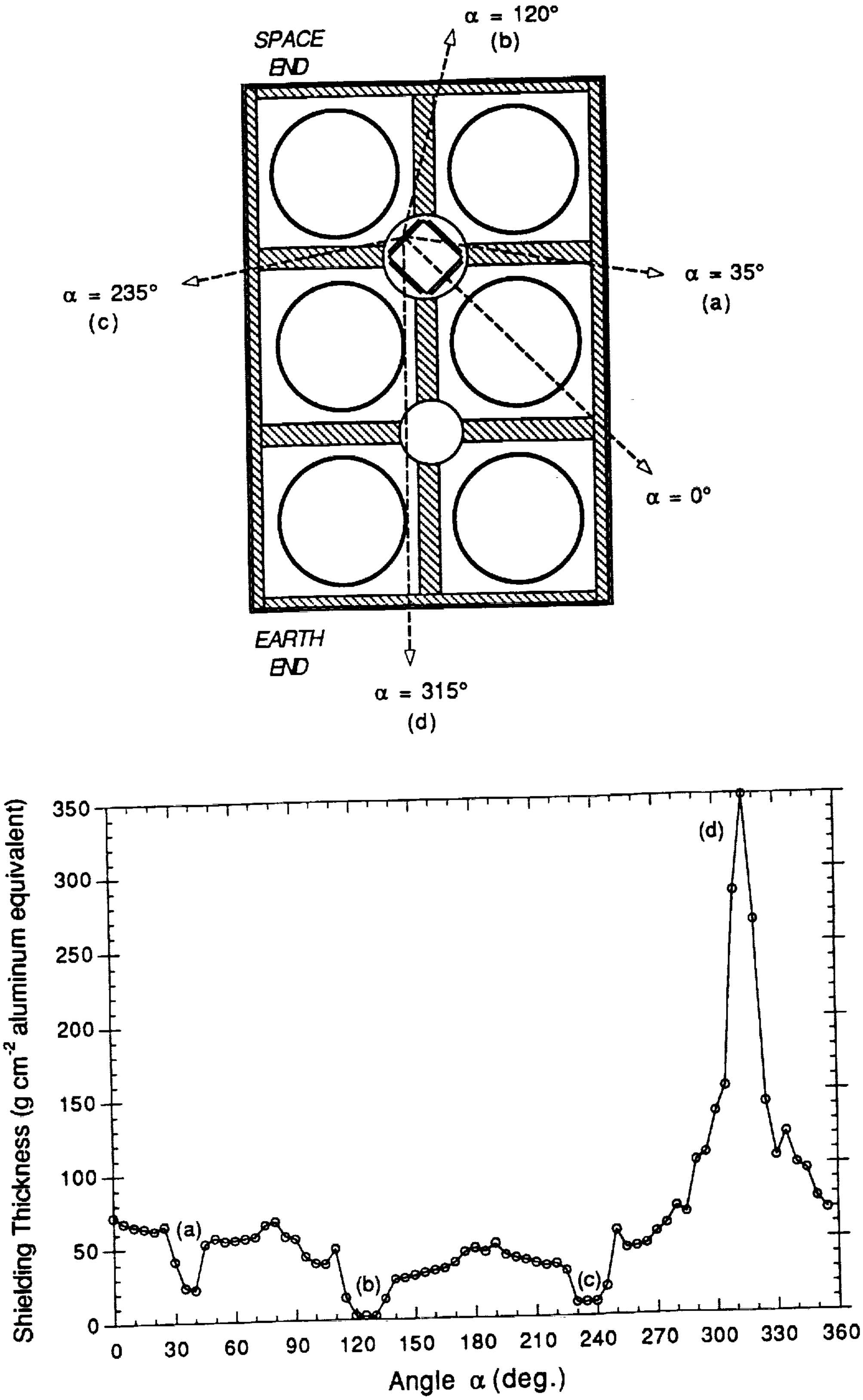


Fig. 5-2. Shielding distribution in horizontal plane for a point on surface of side PNTD detector module of Exp. P0006.

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