

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

ADA 087752

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 4275	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A DEMONSTRATION OF SATELLITE SHIELDING		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. B. Langworthy		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N; RR0120141; 66-0439-0-0
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE July 22, 1980
		13. NUMBER OF PAGES 25
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		16a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		Accession For NTIS GR&I DDC TAB Unannounced Justification <input type="checkbox"/>
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		By Distribution/ Availability Codes Dist. Avail and/or special A
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Satellite shielding Electron shielding Sector analysis dose		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A capability of performing electron shielding design for a real satellite is demonstrated by first posing a typical shielding problem and then solving it using the recently developed codes, SECTOR and BRANDE. In the process a modeling technique is introduced which allows conceptualizing the geometrical complexities of satellites in such a way that the shielding problem is made more methodical than the previous approach, a series of trials and corrections.		

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A DEMONSTRATION OF SATELLITE SHIELDING

I. Introduction

This work on shielding demonstrates the capability of designing minimal weight shielding for a real satellite to a hardness requisite to a given radiation environment. The heart of the demonstration consists of applying to the satellite those procedures to be used in an actual program. There is also preparatory work which needs to be done only once and which generally would not be part of a later program. Then additional requirements of a satellite shielding program will be pointed out. Distinguishing these three components of the demonstration allows its effectiveness to be evaluated.

II. Code and Data Preparation

The two codes used here, SECTOR and BRANDE, were received from J. Janni and G. Radke of Air Force Weapons Laboratory (AFWL), Albuquerque, NM. Predecessors to these codes have already been used to minimize the shielding weight from an Air Force Spacecraft in the natural environment.¹ These codes calculate dose at a point by sector analysis and have been tailored to the needs of satellite shielding design. Their main input, a data deck describing the structure of a typical satellite, had been previously produced for thermal analysis and contained most of the information needed for dose analysis.

A. SECTOR

The code SECTOR² analyzes the material composition of each solid angle sector around a dose point and consists of 35 routines. The processing of the input file data to produce an output file for use by BRANDE will be described in detail. The input file includes: 1) cards describing the structure material composition by atomic constituents; 2) cards describing structure geometry in terms of solid or void elemental volumes which may be combined to any degree of complexity; 3) cards listing points where dose is required; and 4) a card controlling the extent of analysis and printed output. As the geometry input is processed to an intermediate file for the next step, it is checked for proper organization. Upon reading a dose point, SECTOR produces a requested number of rays originating at that point which are all nearly equally separated from neighboring rays. This process is equivalent to a division of the solid angle about the dose point into equal solid angle sectors. All intersections of each ray with any elemental volume of the geometric structure are then obtained and sorted into entrance and exit pairs by material. The material, its thickness in g/cm^2 , and the radial distances to the intersection points are listed in the output file. SECTOR makes a special printout for cases of overlap, that is, where two materials occupy the same segment of a ray. For each dose point a crude total mass for the structure is obtained by adding up the masses within each sector. This total mass is only an estimate. Masses at large radii often get over- or under-emphasized randomly because the presence or lack of mass at the ray position is taken as representative for the entire sector width.

¹Manuscript submitted May 19, 1980.

The SECTOR source deck received from AFWL was about 1260 cards in CDC 6600 FORTRAN. Translating to Texas Instrument Advanced Scientific Computer (ASC) FORTRAN proved very little problem due to the care of the originators in the use of simple FORTRAN. At one point it was necessary to change some constants used for scaling but this caused no change in the results. Some of the intermediate storage provisions which were not used in this work have not been implemented most efficiently. The user's manual² provided three sample problems which were run for verification of the translation process. The translation process was verified to the extent possible by running these three problems.

The originators had turned over a SECTOR source deck early in their preparations for distribution. Some later corrections and improvements were sent and most were implemented here. In addition a change was made to allow the use of a completed geometry file as input for a later run which saves input file processing time.

B. The Satellite Structure Data

The data deck describing the satellite structure for thermal analysis purposes represented a 4 man-month investment. It was therefore worthwhile to spend another man-month on translation, rather than attempt to work up the data from satellite drawings. The necessity for translation arose because the thermal and sector analysis efforts were independent and used different elementary volumes and file formats. This work went exceptionally smoothly considering its overall complexity.

In translating, it was necessary not only to change the numerical data appropriate to the original elemental volumes to that required by SECTOR but to reorganize the descriptive part into solid-void groups. The latter required duplicating and inserting cards, a cumbersome process on the keyboard editor of the ASC. To avoid this, the deck was transferred as a tape file from the originating computer to the DEC-10 and from there to the ASC. These two transfers required only character set translation. While on the DEC-10, the TECO editor was used to reorder cards, leaving numerical translation for the ASC. After extensive manual editing, an edit routine was written in TECO command language which searched text for certain label cues, copied the cued elemental volume consisting of from one to four cards depending volume type, changed the label, and inserted the copy as new text. Numerical translation was accomplished on the ASC using a short FORTRAN routine written for the purpose by comparing descriptions of the original set of elemental volumes with those required by SECTOR.

After translation, information describing the material of each solid elemental volume was added. This step was also mechanized. Because of limitations in BRANDE to be described below and because of limitations in the detail of available information, it was necessary to describe the entire satellite as consisting of aluminum in various densities. While this is possibly a descriptive inadequacy, the error introduced has no effect on our demonstration. For demonstration any representative description would be sufficient. The interior of all electronics boxes was thus designated a homogeneous "electronics" medium, the uniform density of which was to be determined later.

Table I
Edit History of the Structure Data File

<u>Step</u>	<u>Number of Cards</u>
Original file	636
TECO edit	821
Numerical edit	1350
Shield edit	1661

The file edit history is briefly indicated in Table I, the last step being described below. The volume of data manipulated may be surmised by noting that every card of the original file had six position figures given in inches to an ostensible precision smaller than 0.001 inch (1 mil). The manipulation of this data was not only nearly error free but about 50 errors in the original file were discovered and corrected. This process and the subject of file accuracy are treated below. The number indicated for the original file ignores about 500 cards devoted to the geometry logic. This information was incorporated in the solid-void groupings and that section of data was deleted.

C. BRANDE

The code BRANDE calculates dose at points analyzed by SECTOR and the version used here consists of eight routines. The input file from SECTOR is a list of the materials and their thicknesses in each sector surrounding the designated point. BRANDE uses internal tables of number and energy transmission coefficients derived from TIGER,³ a descendent of ETRAN. Since the version of TIGER used has slab geometry, a procedure indicated by T. M. Jordan⁴ has been applied by G. Radke to transform these coefficients to an intermediate geometry, that of a spherical shell, which, for appropriate dimensions, lies between the extremes of slab and spherical geometry. The comparison being expressed here is based on solid angle exposure. Thus a point near the surface of a thick slab may "see" as much as 2π steradians; one in the center of a sphere, 4π ; whereas, a point in a thick spherical shell "sees" some intermediate exposure. The calibration to be mentioned below substantiates this procedure. Coefficients so derived are then used to attenuate fluence within each sector in what may be called a straight-ahead approximation. Integrating over all sectors, BRANDE then obtains a dose conversion factor table, which is a function of incident energy. This may be integrated over the incident spectrum by user supplied methods to obtain dose. In view of the approximations in both the sector analysis method and in its implementing procedures it is desirable not only to verify BRANDE itself but to find an upper bound on any error attributable to the method.

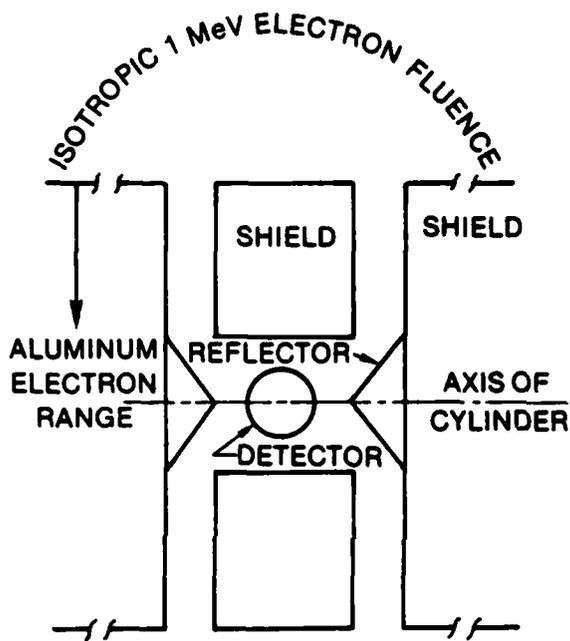
For purposes of assessing the sector analysis method therefore, a test problem was designed to maximize the effects of a deficiency. Since sectors are analyzed independently, electrons scattered out of a sector would be neglected in geometries where there is no averaging due to the entry of

similar electrons from an adjacent sector. Figure 1 exhibits a cross section of the test geometry. Using the code SANDYL,⁵ a physically realistic standard for this purpose, two runs were made counting detector dose with and without the conical reflectors present. If this had shown a higher dose due to the reflectors' action as a source of secondary electrons, the difference would have been a measure of the sector analysis error. In sector analysis these reflector cones cannot act as sources because sectors originating at the detector center and passing through them must go through many electron ranges of shield before reaching source fluence. In other words the sector analysis dose is the same whether or not the reflectors are present.

This test geometry is difficult for Monte Carlo transport codes like SANDYL because of the relatively small volume of the detector and because of its shielded position relative to the source. The test difference obtained was smaller than statistical error. Rather than pursue the answer by statistics reduction, it is held to be a null result for present purposes. Thus, because the shield material and thickness are representative and the 1 MeV incident electron energy is a conservative representation of the requirements for shielding, the null result suggests that unusual geometries will not produce large errors in the shielding problem. Quite likely the expected effect is present but is masked by a background dose due to direct penetration of the shield and due to secondary emission from surfaces other than the reflector.

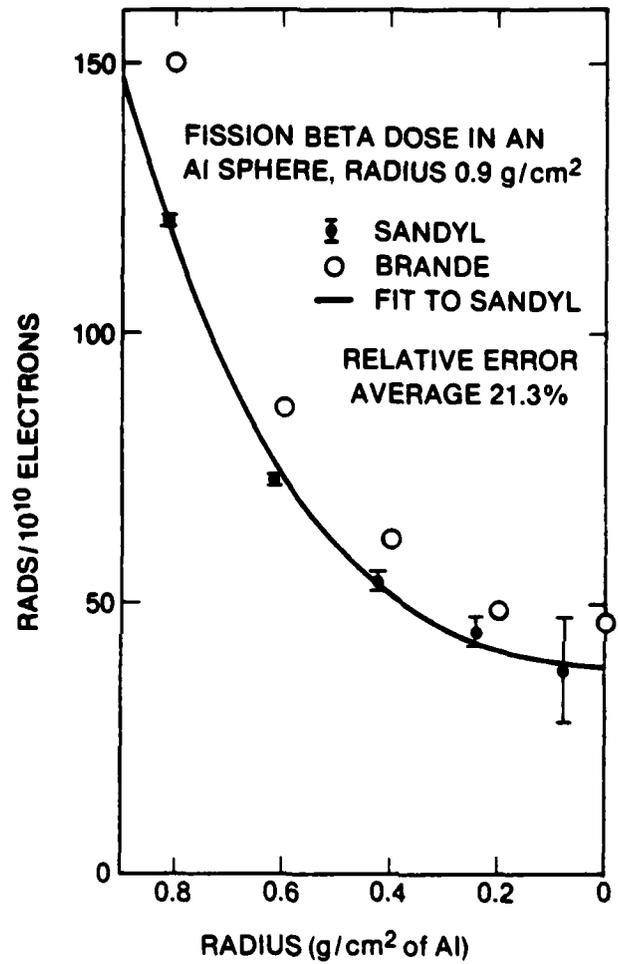
The BRANDE source deck had about 850 cards and its translation was even less problem than that for SECTOR. The version received was a special response to our request and may differ from future versions. In particular all routines to handle dose from bremsstrahlung were omitted. If practical satellite weight limitations confine one's interest to shields of less than 300 mils of aluminum, which is the case here, bremsstrahlung is not a significant contributor. Furthermore transmission coefficients were furnished for only six elements. In a real shielding problem this limitation could be overcome to sufficient accuracy by substituting the nearest available element with a corrected density. In fact in this demonstration the only element used was aluminum. Also the energy range covered by transmission coefficients was 0.1 to 8.0 MeV, just adequate for the selected spectrum. These limitations in the transmission coefficients can be overcome by processing more TIGER data using the Jordan-Radke transformation. The source deck was modified by adding an input spectrum read-in and an integrator, in order to get total dose. Since no sample problem was furnished which could be used to verify translation, verification was made by comparison with SANDYL.

This comparison was made by calculating dose in an aluminum sphere of 0.9 g/cm^2 (131 mils) radius irradiated by an isotropic fluence of fission electrons. The use of fission electrons corresponds to the radiation environment specified for this demonstration and this thickness is in the region of the thicknesses of greatest interest for shielding. This comparison therefore serves the additional function of calibrating BRANDE for its intended use. Moreover the use of the range of radii from the surface of a sphere to its center explores the range of solid angle exposure from 2π to 4π , already mentioned. If BRANDE did not handle exposure geometry correctly, it could be a factor of 2 or more high near the outside,



TEST PROBLEM GEOMETRY

Figure 1



BRANDE CALIBRATION

Figure 2

the same factor low in the center and still have nearly correct calibration on the average.

Comparison results are presented in Figure 2, showing 5 dose points for BRANDE and doses in 5 volume bins for SANDYL. The SANDYL run made 15,000 histories and the statistical error of each bin is shown. The large increase in relative error, reaching 26% at the center bin, shows the meaning of the remark that such geometries are difficult for Monte Carlo codes. These SANDYL points are each plotted at the volume average radius of their respective bins. The BRANDE doses, being point doses, don't require this treatment. Thus to make the comparison, the SANDYL data were fitted to the empirical curve,

$$d_i = a \cosh^4 br_i,$$

where $i = 1$ to 5, and d is dose, r is radius and a and b are determined by the fit to be

$$a = 38.3 \text{ rads}/10^{10} \text{ electrons,}$$

$$b = 0.976 \text{ cm}^2/\text{g.}$$

The power 4 was chosen as giving the best fit in the range of integer powers from 1 to 10. The overall fit exhibits 1.8 rads root-mean-square error. This fit assumed constant errors, however a second fit using the actual errors differed very little. Using points from this curve to calibrate BRANDE gives the results of Table II and an average relative error of 21.3%.

Table II.

Radius, g/cm ²	Relative Error, %	
	BRANDE Calibration	SANDYL Statistical
0.0	21	26
0.2	18	6
0.4	20	3
0.6	18	1
0.8	29	1

Clearly exposure geometry is being handled correctly. Indeed, even a quite small overall trend, inside to outside, is not supported. However the SANDYL data is not giving the firmest test for this effect in view of the large errors of the central points.

While it would be easy enough to correct BRANDE for the average error obtained, it turns out this step would not affect the demonstration. Since BRANDE calculates dose before shielding as well as afterward, only its ability to obtain relative dose is being used. Even though on the basis of this comparison, it seems probable that BRANDE is a good deal more accurate than 10% in relative dose, the comparison needs to be extended to other depths.

III. The Demonstration

Typically a shielding optimization problem might be posed as follows. Given a fluence and spectrum, design the minimum weight shield protecting essential parts of a described satellite to a designated hardness or radiation level. Ordinarily the specific hardness criterion would be imposed, so before this demonstration the controlling quantities were arbitrarily fixed in regions of typical interest in such a way that the problem posed would be non trivial. The isotropic fluence chosen for fission electrons was $10^{16}/\text{cm}^2$. This fluence would correspond to a low-to-moderate-altitude spacecraft operating in artificially saturated earth radiation belts for several days. Estimates of worst case electronics doses were nearly 40 Mrads. Such a dose requires a 180 mil shield to reduce it to 1 Mrad which was adopted as hardness criterion since it is possible that devices hardened to 1 Mrad could be obtained for use in spacecraft. The fission electron spectrum⁶ as a function of electron energy in MeV is

$$dN/dE = \exp(-0.575E - 0.055E^2).$$

As expressed, normalization to one electron needs to be added. The average energy is 1.39 MeV for the spectrum from 0.2 to 7.0 MeV. It should be noted that, at the depths of interest here, it would not be necessary to include so much of the low energy spectrum just to compute dose. However the hardness criterion is in absolute fluence and typically would be meant to include all low energy electrons, that is, to zero energy. If so the approximation terminating the spectrum at 0.2 MeV makes about a 15% normalization error. Such an error would affect any absolute doses stated here but have no effect on other results.

Due to the volume of data required, the description of a complex satellite's geometry is a data processing problem of an extent that requires quality control procedures. For this demonstration it was necessary to execute two aspects of data refinement. Other aspects which could occur will be discussed in Section IV. Certain general considerations of the problem are made next which simplify shield design by suggesting a model. Before designing the shield, a decision is made as to which parts require shielding. A few remarks on model justification complete this section.

A. Data Refinement

As has been mentioned, SECTOR prints identifying information when overlap happens on one of its rays. The user may control this feature by setting the overlap tolerance as part of the input. In all cases to be reported here this tolerance was set at one mil. This is finer than would be required to avoid significant dose errors in the BRANDE calculation but is useful as a check for errors in the data. Examples of the procedures used follow. Starting with the dose point near the center of the satellite and requesting a minimum number of rays, say 120, a list of overlaps was obtained. Many were resolved by inspection since the errors made were obvious. Especially in the beginning the inspection was aided by a sketch of the overlap. Some resolutions required additional information from the satellite blue-prints. Some errors occurred due to faulty translation. A few cases of "false" overlap occurred where the overlap was unexplainable

under the rules in the user instructions. These were avoided by minor alterations. After eliminating each overlap on the first list, the number of rays was increased, ultimately to 2024. In addition, in some cases the dose point was shifted nearer to a region of difficulty or in such a way as to increase coverage at the outer portion of the satellite. In this way nearly all overlaps were eliminated and the average spacing of ray penetrations of the outer skin achieved was less than one inch. As a result of the care exercised in this part only one additional overlap occurred during the dose calculation phase and it was of negligible size.

During the data translation, three aluminum densities had been established to represent the satellite structure. These are listed in Table III. The density of the homogeneous medium representing honeycomb is the average density of the material. The electronics density was fixed at one-third aluminum density. This density seems consistent with known electronic assemblies.

Table III. List of Materials

<u>Material</u>	<u>Density (g/cm³)</u>
Aluminum	2.70
Honeycomb	0.27
Electronics	0.90

B. General Considerations and Model

Based on construction characteristics typical of many satellites it is possible to offer some generalizations in the geometrical dependence of dose which considerably simplify shield design. For the sake of the demonstration these generalizations are used only as a guide and the shield design is independently established by a before and after comparison of dose at many points.

Particularly in the case of spin stabilized satellites, in order to avoid added structural requirements, there is a natural design tendency to concentrate parts. To be definite, suppose the lanes between boxes are smaller than the boxes. Furthermore a common construction feature is a deck on both sides of which boxes are mounted. Since the parts are mostly rectangular parallelepipeds (RPP's) of about the same height, the overall shape tends to be a large RPP. Neglect external appendages and homogenize the entire mass within this box-shape. This model applies to an even wider class of geometries than its genesis implies because in shielding, practical interest is mainly in thicknesses up to 2 g/cm² or 300 mils of aluminum. This implies that there is an inner volume which is of no interest because it is self-shielded. To make this specific, assume a satellite body weight of 500 lbs. with an overall density of 1/6 that of aluminum. This would give a volume of 33,300 in³ and dimensions of about 32 in. for a cubic body. A 2 g/cm² shield at this density is close to 2 in. thick so that the self shielded volume is 30³ or 27,500 in³ which is 82% of the

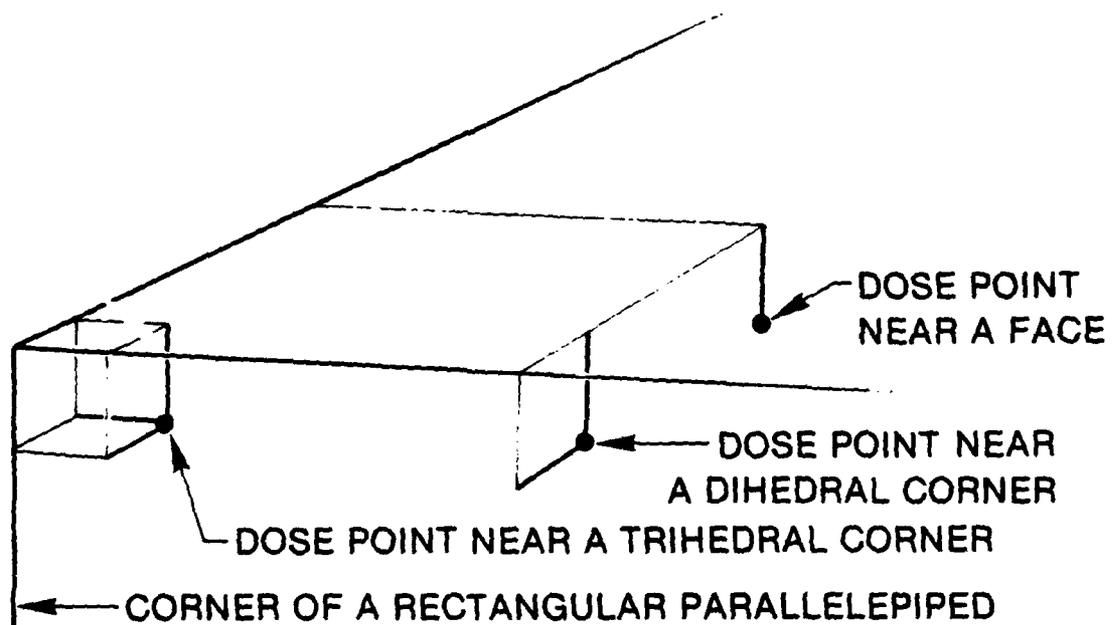
satellite model volume. In a real satellite with its boxes and lanes this volume would be quite irregular and would bear a smaller proportion to the total. However as will be clear shortly, its mere existence allows certain freedoms. These concepts imply the design dictum: "Place soft or critical boxes as close to the center of gravity as possible."

It is clear that the RPP model presents only three unique geometries for dose points: faces, dihedral corners, and trihedral corners, illustrated in Fig. 3. The solid angle exposure of every model point may be related by continuity to one of these geometries and the first and last are extremes. Points near faces have a maximum exposure of 2π steradians and points near a trihedral corner, $7\pi/2$. In reality there may be cases where exposure is greater, for example, dose at a point in a needle-shaped object but in the structure file no such objects occur. Also there are lots of situations of concave geometry ignored by the model, however, it is clear on the basis of exposure that only convex geometries have higher dose than the familiar geometry-neutral approach, slab geometry. For any particular dose point there is some cone of solid angle through which most of the contributing fluence enters, the cone of significant exposure. Every point is backed up by the self-shielded volume. Thus any two points separated laterally by some distance, say, twice their depth, may be considered independent in the sense that shielding one need not affect dose at the other. In the real geometry there is no need to place test dose points closer than this.

In dosimetry there are many situations in which intervening voids may be ignored. In electron hardening problems there is an even wider latitude since generally threat fluences are not known to better than a factor of two. Attempting accuracies better than 20% is therefore superfluous at best and may be wasteful. In addition, the averaging effect which occurs by integrating over all contributing solid angle to obtain dose provides great freedom to ignore the effects of voids. Considering each of the three model geometries separately, a uniform outer layer may be separated any distance without affecting dose at an interior point. One could even change the shape of this outer layer and incur a shape factor penalty. However this latter generalization will be avoided in the following since the model will be used only for relative dose estimates. For example, the dose reduction factor due to an added shield layer inserted between two separated layers will be obtained. The use of "diffused" densities for the honeycomb and electronics materials is justified by these same considerations.

Table IV. Ratio of Corner Dose to Face Dose

Corner	Depth (mils)	
	50	300
Dihedral	1.83	2.32
Trihedral	2.50	3.64



THREE DOSE POINT GEOMETRIES

Figure 3

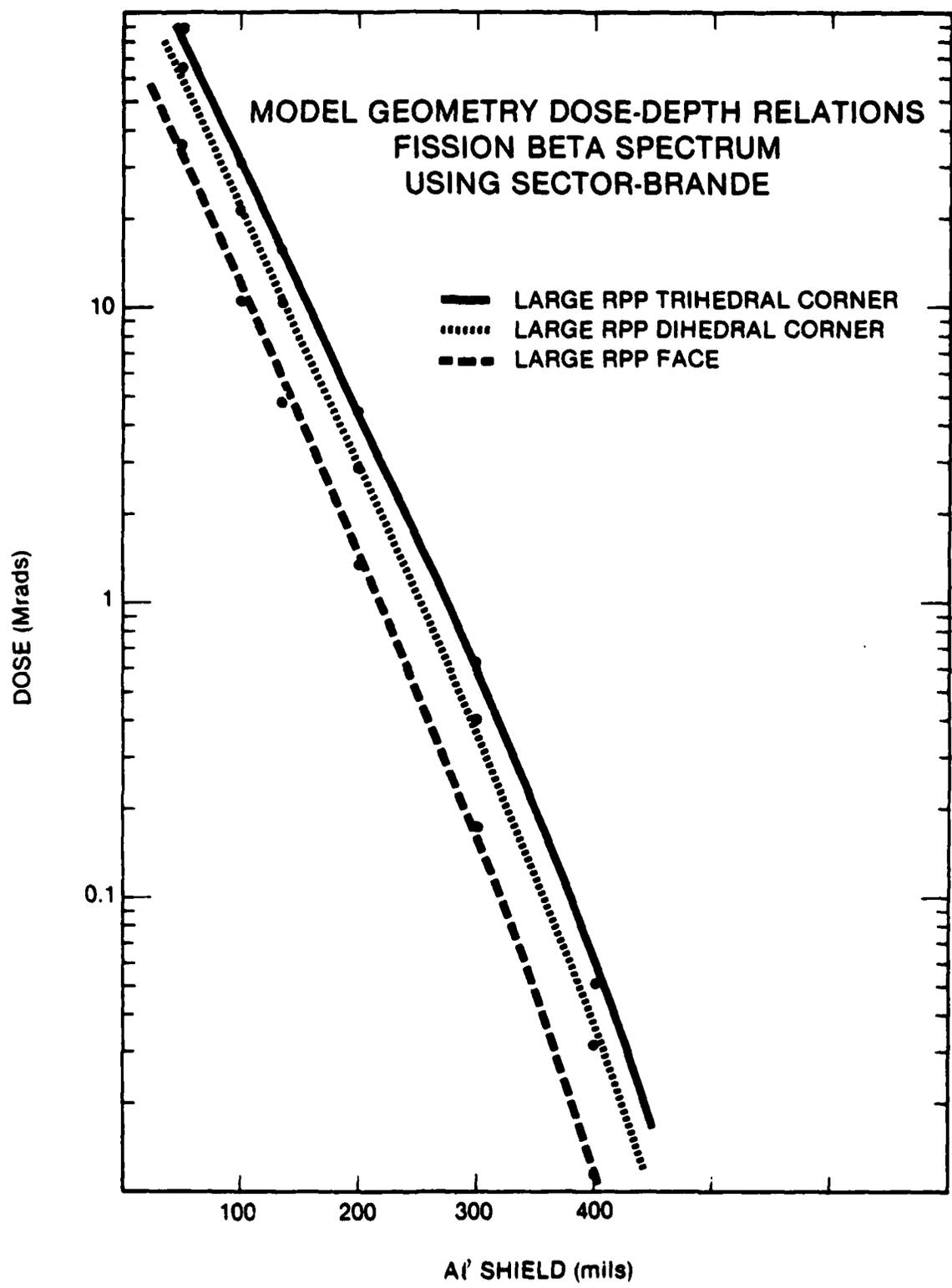


Figure 4

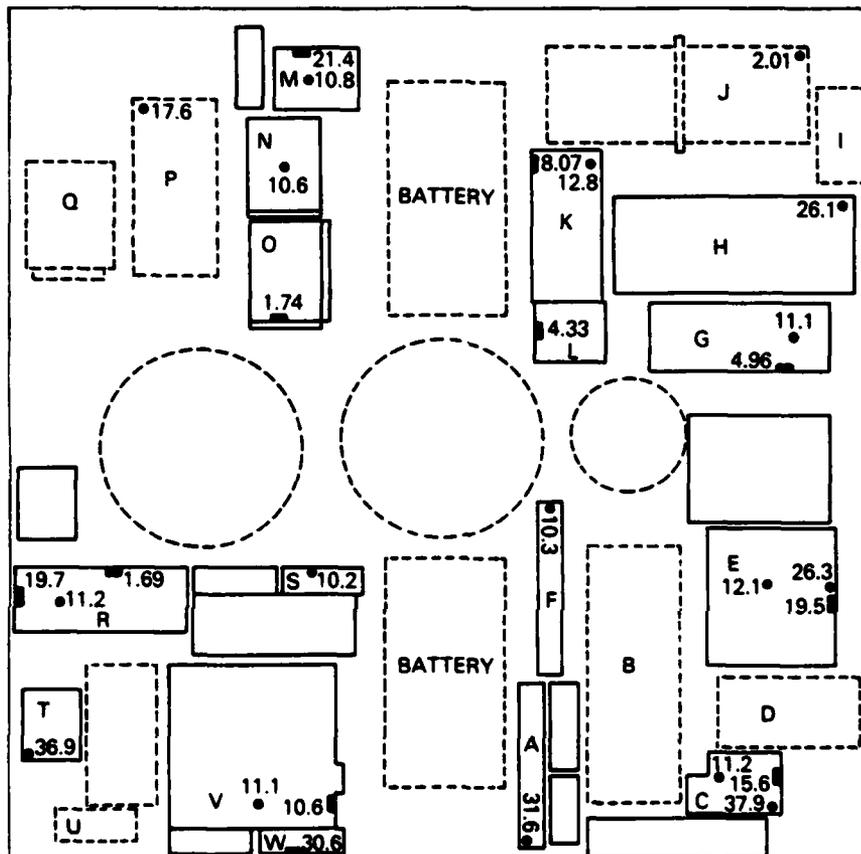
Dose-depth curves were obtained for each of the three geometries by making SECTOR-BRANDE runs on an RPP. From the foregoing its dimensions are arbitrary so long as they are much larger than the greatest depth of interest. Indeed, because the three geometries are dimension independent, they are the model rather than a specific RPP. The density is arbitrary if depths are measured in g/cm². The results are shown in Figure 4 with depth in mils of aluminum shield. It is remarkable that these curves are nearly flat exponentials and nearly parallel over the region of interest. This allows the following empirical rule: dihedral corners get twice the face dose and trihedral corners, three times the face dose. The actual figures in Table IV expose the rule's accuracy, about 20%. This crude rule enjoys a too perfect explanation by the equally crude notion of cone of significant exposure. If the cone's apex angle is not much more than 45 degrees, then at a dihedral corner two such cones add at the dose point and at a trihedral corner, three. The rule allows a design dictum: "Avoid placing soft chips in exposed corners." It is obvious from Figure 4 that BRANDE neglects bremsstrahlung since its presence would cause these curves to flatten out near 400 mils.

C. Survivability Assessment

The extent of the demonstration was tailored to available time by concentrating efforts on the equipment on the top of the deck of the representative satellite used in this sample calculation. This equipment occupies about 43% of the total volume occupied by deck mounted equipment. Figure 5 shows which equipment was shielded in a plan view of this area. Non-electronic equipment was not shielded. Six boxes B, I, J, P, Q and U were not shielded as shielding them was assessed as not critical.

D. Shield Design

The main features of the model confer certain general features to the shield. In the absence of detailed knowledge for any particular electronics box that soft parts were systematically excluded from its exposed corners, all exposed corners require extra shielding relative to exposed faces; trihedral corners, more than dihedral corners. The thickness of the extra layers and of the face shield may be determined from Figure 4 after first establishing an effective skin thickness (so called because it averages all exterior features, mainly skin, over solid angle). The procedure is to take the dose for a model geometry point in the satellite structure at the inside surface of an electronics box and get the total thickness producing this dose from the corresponding model geometry curve of Figure 4. Subtracting the box wall thickness leaves a residual, the effective skin thickness. Points chosen should be points with the cleanest geometry, i.e., geometry most resembling a model geometry. Besides this advantage in identifiability, a trihedral corner has another advantage over the other two since it averages over more solid angle. Moreover for this model geometry, cleanest is equivalent to highest dose, which from Figure 5 is 37.9 Mrads. Referring to Figure 4 this results in an effective skin thickness of 92 mils. One also sees that a 180 mil shield in addition will reduce this dose to the required level. Furthermore a dihedral corner needs 25 mils less and a face needs 55 mils less. The thicknesses actually used were 3 mils greater



PLAN OF DOSE POINTS AND SHIELDING

- DOSE POINT AT THE TOP INSIDE SURFACE
- DOSE POINT AT THE SIDE INSIDE SURFACE
- SHIELDED EQUIPMENT
- - - NONSHIELDED

DOSES SHOWN IN Mrads DUE TO AN ISOTROPIC FLUENCE OF $10^{16}/\text{cm}^2$ FISSION ELECTRONS

DOSES BEFORE SHIELDING

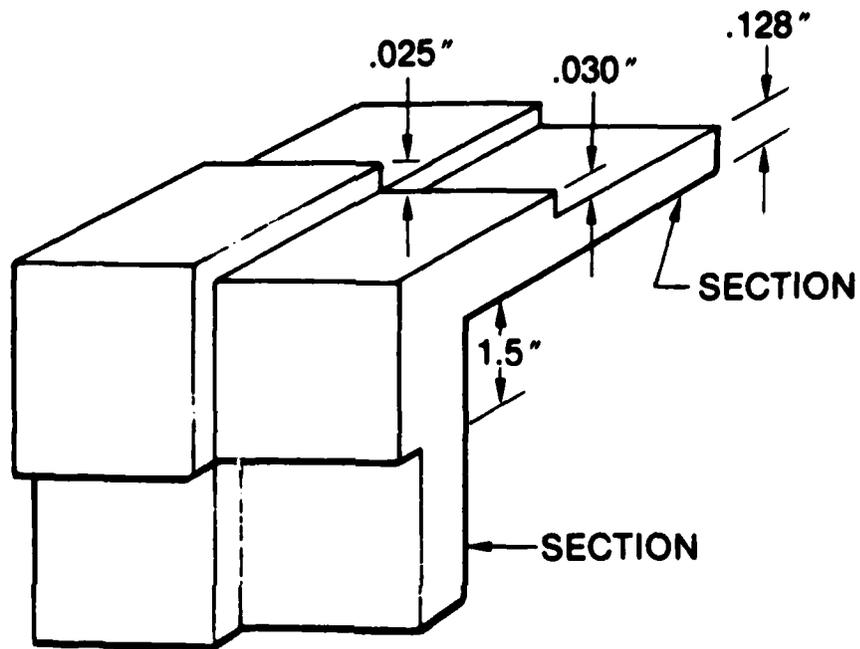
Figure 5

that is, 183, 158, and 128, respectively. It should be remarked that in this preliminary check to determine effective skin thickness, only a few points were run. The before shielding picture of Figure 5 was done later to complete documentation.

What determines the shield width on the two types of corners? A quite conservative approach is to cover the range of interest for shielding in the diffused electronics medium, that is, 1 inch, and enough more to cover the cone of significant exposure, say, another 0.5 inch. The difference between 1.0 and 1.5 inches width turns out to change total shield weight by only 7% so a more detailed determination was not made. This argument actually justifies contouring the thickness to zero over this width but contouring could cause fabrication problems. Thus the thickness was held constant at the maximum required. Figure 6 shows how the various layers of shield would appear if sectioned about 3 inches in each direction from a trihedral corner. It should be pointed out that this approach could use the actual electronics density of the specific box shielded were it available.

Applying this model shield to the satellite structure file required about 150 elementary volumes or pieces of shield which were inserted by a manual edit of the data file. Insertion of this much data of course requires a quality control effort. Since by this point a facility in picking out relevant dimensions by inspection had been developed, perhaps the main problem was adjusting the shield dimensions to meet properly at corners without overlap (in the sense defined above). A shortcut was used which allowed this process to be done mentally. All shield pieces were given a constant thickness of 50 mils, and the density was then adjusted to achieve the design thickness. For dose purposes this is completely equivalent to using the design thickness directly and it saves much work. This is the shield edit referred to in Table I. Overlap check showed 9 errors in this edit and these were eliminated.

Test points were chosen to check the model and to show whether or not the design goal of 1 megarad maximum dose had been achieved. These are listed in Table V and are shown in Figures 5, 7 and 8. Each point was placed at an inside surface of the indicated box since the hardness criterion is for external dose to an electronics device as normally packaged. Of a total of 28 points, 18 were chosen to check model geometries, 8 at points not covered by the model (those labeled "inside"), and 2 at non-shielded points. The results of SECTOR-BRANDE runs on these points after the shield edit are given in the column labeled "Model" and in Figure 7. It was immediately apparent that face points may be divided into those above 1.0 Mrad and those below. Furthermore this classification corresponds physically to those on side faces and on top faces, respectively. Because of this, it was discovered that nearly all boxes were constructed with 62 mil tops and 40 mil sides. Based on this a final model shield was set up with 210, 180, and 150 mils for the three thicknesses on side exposures and 180, 150, and 120 on top exposures. The complete final shield contained, as well, a number of corrections to the shield near individual points, especially the "inside" points. The first model shield had weighed 11.71 lb. and the final, 11.93 lb. Runs of SECTOR-BRANDE on this final shield gave the results labeled "Final" in Table V. The design goal was achieved within 2% on all 26 shielded test points.

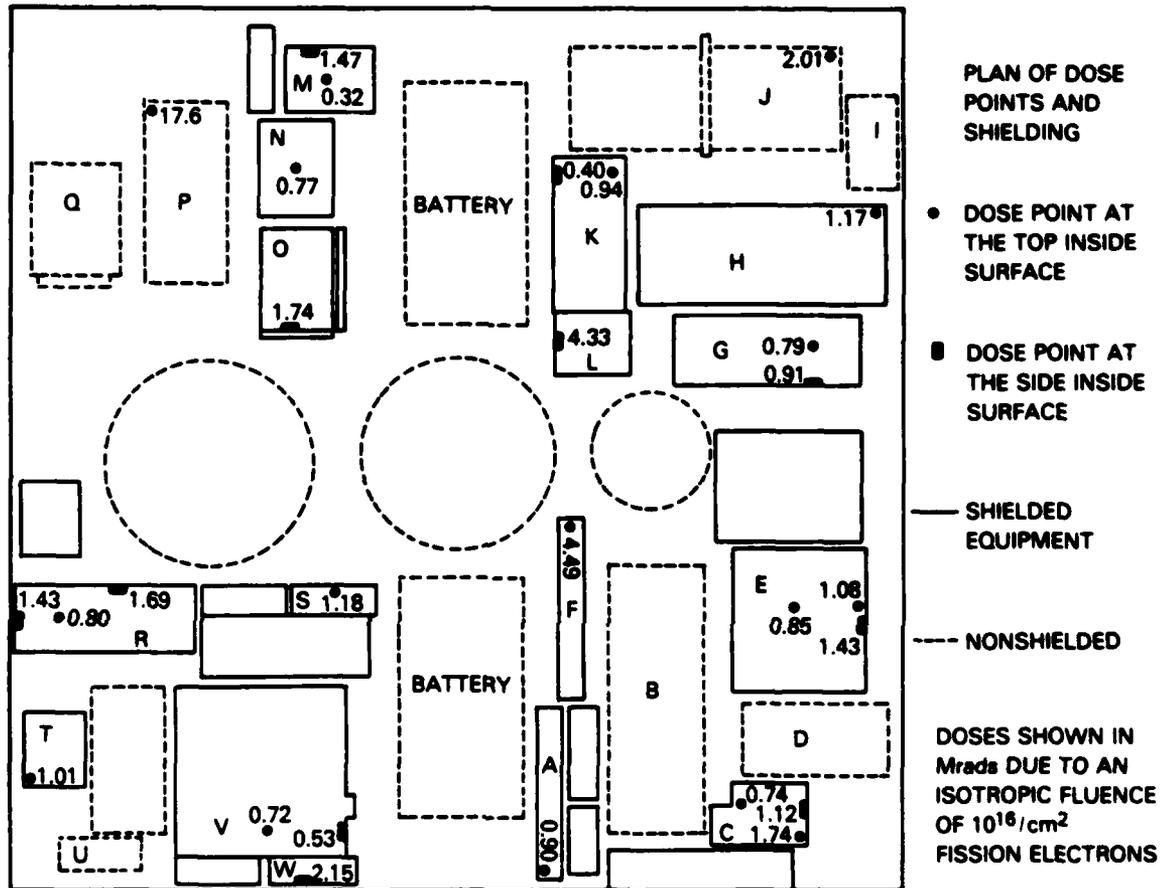


MODEL SHIELD NEAR A TRIHEDRAL CORNER

Figure 6

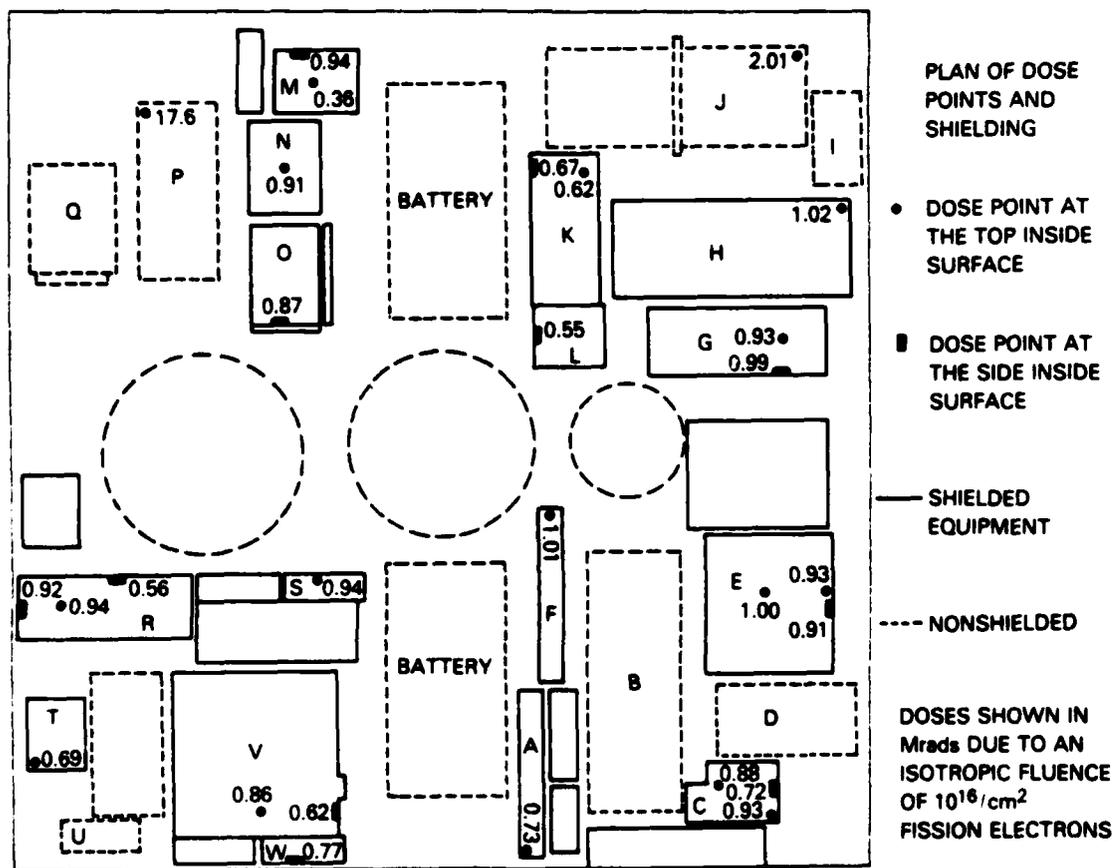
Table V. Doses (Mrads) at 28 Test Points

<u>Point</u>	<u>Box</u>	<u>Shield</u>			<u>Point</u>	<u>Box</u>	<u>Shield</u>		
		<u>None</u>	<u>Model</u>	<u>Final</u>			<u>None</u>	<u>Model</u>	<u>Final</u>
Trihedral	A	31.6	0.90	0.73	Dihedral	E	26.3	1.08	0.93
Corner	C	37.9	1.74	0.93	Corner				
	H	26.1	1.17	1.02	Top	C	11.2	0.74	0.88
	T	36.9	1.01	0.69	Faces	E	12.1	0.85	1.00
Side						G	11.1	0.79	0.93
	C	15.6	1.12	0.72		K	12.8	0.94	0.62
	E	19.5	1.43	0.91		N	10.6	0.77	0.91
	M	21.4	1.47	0.94		M	10.8	0.32	0.36
	R	19.7	1.43	0.92		R	11.2	0.80	0.94
Face	W	30.6	2.15	0.77		V	11.1	0.72	0.86
					Inside	G	5.0	0.91	0.99
Not	J	2.0	2.01	2.01	Face	K	8.1	0.40	0.67
Shielded	P	17.6	17.55	17.55		L	4.3	4.33	0.55
						O	1.7	1.74	0.87
Inside	F	10.3	4.49	1.01		R	1.7	1.69	0.56
	S	10.2	1.18	0.94		V	10.6	0.53	0.62



DOSES WITH MODEL SHIELDING

Figure 7



DOSES WITH FINAL SHIELDING

Figure 8

Linear extrapolation of this final shield weight to include shielding of the equipment on the bottom of the deck based on potential shield area gives a complete shield weight of 25.5 lb., which is 6.4% of the assumed unshielded satellite body weight of 400 lbs. A judicious average using Table V gives a no-shield dose of 18 Mrad. Together with the near exponential behavior of the model dose-depth relations, this yields the thumb rule: each power of ten dose reduction increases weight 5%. A naive application of a 183 mil shield to the potential shield area, an RPP of dimensions 32 x 32 x 14 (which already includes some reduction for non-shielded area), would have resulted in a shield weighing 68.2 lb. Thus a 63% shield weight reduction has been demonstrated. Again, compared to this naive approach, use of the model may be said to save 25 mils over the dihedral corner shield area plus 55 mils over the face shield area. This would weigh 3.92 lb. so use of the model saves 25% of the weight of a single 183 mil shield covering only the shielded area. Of the total percentage saved, that saved by the model is 16%, leaving a remainder of 47% which is saved by not shielding the entire potential shield area. Since in Section C no special effort was made to achieve minimum shield area, it is clear that shield weight reduction is strongly dependent on shield area selection, that is on the choice of critical boxes. Clearly placing non-critical boxes in such a way as to block exposure of the critical ones at an earlier design stage would reduce the area that had to be shielded and the shield weight. In some cases it may be possible to avoid the necessity of shielding by this process.

E. Model Utility

In the foregoing, the model offers a first prescription for the application of shielding. To see its value as a guide, imagine the use of trial and error to establish the thickness of 150 pieces. This process would require one or more test points for each piece and more iterations of the adjust-retest cycle to achieve the required dose levels. Thus in its present use the model is already quite valuable. Even so, a close reading of Table V provides justification for extending its use. First note that those 18 points chosen to be model points either fall automatically into three classes by magnitude or else there is a reason why they don't. The point in box A has extra shielding by a device mounted in the skin just outboard. The point in box H is shielded by box I. The point on the side face of box C is shielded by box D. Box W had only a 20 mil skin. As already mentioned, the fact that the face class divides into two, led to noticing the greater thickness of the tops of boxes. A numerical test, comparison of class dose ratios, is precluded for faces since there are two effective skin thicknesses. However, this can be done for corner points since they average over the top and side exposures. Thus from the high trihedral corner reading, the average effective skin thickness of 92 mils was already obtained. For this thickness Figure 4 gives a dihedral corner dose of 26.0 Mrad, comparing very favorably with the box E point at 26.3. In sum the apparent gross average of the homogenizing process used to generate the model is strongly affirmed as an effective procedure. This justification is sufficiently strong that the model could be used entirely on its own, given an effective skin thickness. Of course SECTOR-BRANDE would still be necessary for non-model points.

It is worth pointing out explicitly that the use of the model to get relative doses, that is, dose reduction factors, by the use of an effective skin thickness to make connection with the external fluence, is its most accurate use. Possible use of the model to get absolute dose based directly on external fluence may be subject to shape factor errors of 50% or more. This is made clear in Table VI, an analysis of the two classes of face doses using Figure 4 to get the effective skin thicknesses. The unresolved part may generally be called shape factor effects but it is possible to be more explicit. In the case of the top face points, there are at least 2 pieces of equipment mounted near the top skin which cast irregular shadows and so were not included in the known skin thickness. Similarly the side points are shadowed in a complex way by paddles extending from the corners. Neglecting this unresolved part for the top case gives an over-estimate of dose by about 50%.

Table VI. Partition of Effective Skin Thickness

	Side	Top
Average Dose (Mrad)	20.2	11.2
Eff. Skin Thickness (mils)	74	103
Known Skin Thickness	55	78
Unresolved Remainder	19	25

The small variation of weight between the model and final shields, in spite of the extensive thickness changes between the two, suggests another possible use of the model. The easily calculated model provides a total shielding weight accurate to a few percent.

IV. Further Requirements

Consideration will now be made of all requirements which a complete fission-beta shielding program could impose in addition to those demonstrated.

A. Data Processing

It is easy to imagine that a more detailed structure description than the thermal analysis data used would be available. However if the shielding requirement is not more detailed than that imposed here, the input need not be more detailed either. This is because the shielding criterion has been met at the least shielded points where electronics might encounter it. It might be required to check dose to an individual chip inside a box. In this case details of the surroundings of the chip would be required. Such increased detail is a capability of the techniques demonstrated and thus require no additional consideration.

Developing the structure data directly from blue prints could be a requirement. Besides increased workload, the indicated capability is the same as for the following consideration. The demonstration did ignore certain aspects of data verification that should be observed. No direct comparison with blueprints was made. The number of errors uncovered just by overlap checks makes it obvious that a method of checking with an original data source should be required. An obvious approach is the use of computer graphics to present views which allow this direct comparison. A considerable development of the necessary techniques in computer arts is available. After familiarization there should be no difficulty integrating these techniques with the present approach. Computer graphics could also have been useful in the resolution of overlaps and in the shield edit.

B. Codes

When their respective limitations are not understood, the use of a calculational mechanism is even more dangerous than the use of a physical one. In the latter case intuition whetted by experience may be a reliable guide, but few mathematicians would claim reliability for their guesses as to the limitations of an algorithm. It is therefore necessary that reliance on the use of codes be backed up by a sufficiently coherent theoretical understanding of the techniques that limitations in use due to inaccuracy or inapplicability are completely circumscribed. Lacking this understanding of SECTOR-BRANDE or of sector analysis, it was shown empirically for the region of the intended application that actual inaccuracies were acceptable. This rather brief effort wasn't fortunate enough to encounter limitations so they are still not understood. Both the empirical and theoretical approaches need to be pushed to a point where they agree on limitations.

Use of codes can be expected to entail maintenance effort. The false overlap indications obtained in the use of SECTOR were saved for later analysis since this may uncover minor coding errors. Also another productive use of SECTOR-BRANDE of about the extent used here would justify some time spent optimizing these codes to save computer time.

C. Survivability

The process of assessing survivability was abbreviated in the demonstration. In a complete program there should be an assessment of the hardness of each electronics box and an assessment of the mission criticality of each. The decision of which boxes to shield is then based on both of these elements.

D. Workload

Table VII shows an analysis of six month's work contributing to this demonstration. While the first two phases are one-time efforts and would not be part of a complete shielding, the other phases would be. Code translation includes the BRANDE calibration and the test problem. Data translation includes one man-week liaison with the data source. Data refinement includes a man-week of drafting. Problem overhead is planning meetings and monthly

reports. From this it is apparent that the bulk of the work is data manipulation. The addition of a requirement to develop the data within a limited time could easily exceed our resources in personnel, however in this case a contract for data development could be arranged. Many questions concerning the data were resolved arbitrarily here with no loss to the demonstration. Whether a contract is involved or not, a complete program requires more complete use of original data. Because of this curtailment of details, total times figured from Table VII should not be considered representative of a complete problem. Computer time for this work cost \$1.5K, hardly significant compared to personnel time.

Table VII. Distribution of Time

Phase	Man-weeks
Code Translation	4
Data Translation	5
Data Refinement	6
Shield Problem	3
This Report	8
Problem Overhead	2
Total	28

V. Evaluation

The shielding demonstration itself achieved its non-trivial goal and along the way considerable spin-off of value in this and related programs was generated. The use of the model geometry as an intermediary which both generalizes shape and suggests specifics of shield design was an especially cost-effective procedure. Moreover the conceptualizing power of these modeling techniques has become clear: they allow an assessment of the importance of details so that some may be emphasized and others ignored. Quite likely this same approach will work on satellites of other shapes. In future problems like this one, the model could be extended to include the larger lanes between boxes to allow application to "inside" points. A number of suggestions were made for pre-shielding methods of hardening.

While numerical comparison of these results to those of a similar AFWL program¹ would be desirable, the large number of variables affecting the shield weight probably precludes this. Presenting shield weight as a fraction of total satellite weight is a first step in comparability and presenting it on the basis of dose reduction factor is a second. On the other hand the effects of differences in satellite configuration and in levels of circuit criticality may be just as important but are not as easily quantified. Furthermore while the AFWL program cited has a similar threat in that it also requires shielding against energetic electrons, it differs in considering only natural sources which have a much softer spectrum.

On the basis of Section IV, extending the demonstration to include the points omitted would have considerably extended the workload while adding only minor capabilities to the major ones demonstrated. It is concluded therefore that the capability of satellite shielding has been effectively demonstrated.

Acknowledgments

The author wishes to thank J. C. Ritter for suggesting and supporting this work, C. S. Guenzer for necessary input and helpful conversations, R. M. Farr and R. C. Beattie for drafting, and J. F. Janni and G. Radke for providing the necessary tools.

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