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ERRORS IN GLASS PHOTON TRANSPORT CALCULATION

INTRODUCTION

A calculational capability for photon sources and photon transport in a reactor lattice was added to the GLASS[1] system in 1973. The calculation has been used in a variety of applications since 1973, and has always produced results that appear reasonable. The GLASS photon transport calculation, however, was never compared to an independent photon transport calculation at any state of its development. Recently, the GLASS calculation was compared to calculations performed by the SHIELD system module SNONE (SHIELD system version of LASL DTF-IV[2] code) and significant differences were found in the calculation of deposited photon heat. This led to discovery of certain errors in the GLASS calculations, as discussed in this report.

SUMMARY

Errors were discovered in the GLASS photon transport calculation which can account for as much as a 100% error in redistributed photon heat in a reactor lattice calculation. These errors were discovered while comparing GLASS calculations of the MARK 42 assembly (120 hrs. after reactor shutdown) to SHIELD[3] system calculations with module SNONE for geometries that can be well represented by both calculations. These comparisons are shown in Table I.

The errors in the GLASS calculations were traced to modules PCRISP (Photon Cross Section Processor Module) and PFIST (Photon Fine Structure Flux Calculation). The errors were corrected by reducing the PFIST calculation to the P_o scattering approximation which is adequate for most reactor lattice photon redistribution calculations, and by correcting errors in constants in the PCRISP module. These new modules were installed into the standard GLASS calculation on October 27, 1980 after notifying users of these changes on October 10, 1980.

The effects of the GLASS errors on US2 shutdown heating were evaluated[4] and found to have no impact on charge operation.

DISCUSSION

In February, 1979 an addition was made to the GLASS photon transport calculation that permitted it to read fixed photon sources from SHIELD system records. This was a temporary arrangement to permit use of GLASS to calculate photon redistribution heating using SHIELD system photon sources because SHIELD system S_n transport modules were not available at that time to perform the calculation. The combination of SHIELD system sources and GLASS photon transport were utilized to calculate redistributed photon heating after shutdown for both US1 and US2 assemblies.

In June, 1980 the SHIELD system S_n transport module SNONE (based on the LASL DTF-IV code) had been checked out and could perform photon redistribution calculations with the same sources and cross sections as the GLASS calculation. The GLASS photon calculation, in addition, had several mathematical assumptions that needed checking while the S_n modules treated these same assumptions more rigorously. These GLASS assumptions were:

- Anisotropic scattering represented by a transport corrected P_o calculation.
- Use of cosine current methods for flux and current continuity at zone boundaries in and between lattice cells.

I. Test Comparisons between GLASS and SHIELD

A test problem to compare the two calculations was supplied by J. L. Jarriel and consisted of a MARK 42 assembly in air 120 hrs. after shutdown of the P11.4 subcycle. In these calculations the boundary conditions (in GLASS and SHIELD) were provided by a heavy absorber ring (pure uranium) at a distance of 30 cm from the center of the assembly. This geometry could be represented well by both calculations.

Two sets of photon interaction cross sections were available for use in these calculations, and both sets were used. These cross section sets are the following:

- MULTIGRP photon version ENDFB022 - cross sections processed in 1974 from ENDF/B-IV by the JOSHUA Basic Data Analysis Subsystem (BDASS).[1] The data is in 22 energy groups based from a group structure recommended by the CSEWG Shielding Subcommittee.

- MULTIGRP photon version ANISN58 - cross sections from the Defense Nuclear Agency (DNA) standard library[5] processed from ENDF/B-IV by ORNL. The data has 21 photon energy groups chosen to represent DNA reactor shielding requirements.

The results of these calculations are shown in Table I. The conclusions drawn from these calculations were the following:

- GLASS acieves energy balance with ENDFB022 data - SNONE does not.

- SNONE achieves energy balance with ANISN58 data - GLASS does not.

- A difference of total photon energy exists for the two versions of data. ENDFB022 data shows 6.9% less total photon energy than ANISN58 data.

- SNONE calculated photon heating in the MARK 42 fuel tubes is 80% higher than GLASS with ENDFB022 data.

- SNONE calculated photon heating in the MARK 42 fuel tubes is 5% lower than GLASS with ANISN58 data.

- Angular anisotropy is not important since essentially no difference is seen in P_1 and P_3 calculations with SNONE.

A minor modification was made in GLASS Module PPROD to permit it to utilize the ANISN58 data in the above calculations. Photon production data (from neutron interactions) is loaded irrespective of whether a neutron transport calculation is performed or not. Module PPROD did not recognize production matrix type 'TOTAL' which contains this data in the ANISN58 data. This was a very ninor modification and was implemented without problem or interference to any user.

Two basic questions arose from the results in Table I:

1. Why is there a difference in total source energy for the two MULTIGRP versions?

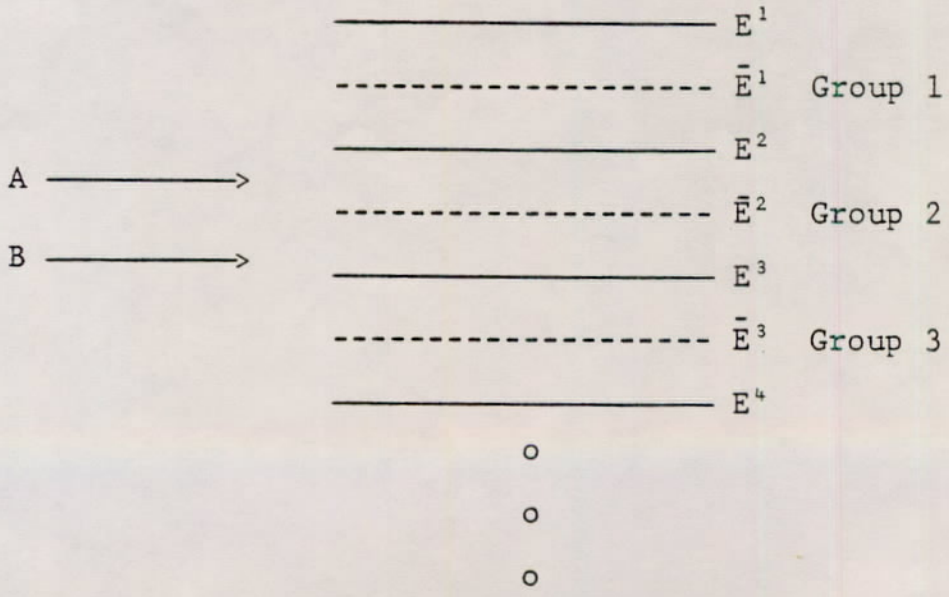
2. Why is there a difference in photon heating results for one MULTIGRP version?

II. Library Data Inconsistencies

The first question was answered by considering the SHIELD system calculation of photon sources. In this calculation discrete photons emitted by many fission products are summed in multi-group form to create an aggregate material photon source. The multigroup spectrum for each fission product was formed by considering each multigroup as a bin and by assigning each photon of energy E such that

$$E_l^g < E \leq E_h^g \quad (E_h^g \text{ and } E_l^g \text{ the high and low energies of multigroup } g)$$

to the g^{th} group. In use, however, all photons in a group are considered to have the average energy ($\bar{E}^g$) of the group. This is illustrated in the following diagram.



A discrete photon can enter the group above or below the median group energy as in A or B above. All photons in a group are assumed to have an average energy of $\bar{E}^g$. If many decays and fission products are summed, the average discrete photon energy in a group will be very nearly $\bar{E}^g$. However, at long times after shutdown only a few fission products contribute to each group. Hence a definite bias above or below the median energy and a shift of apparent total source energy can occur depending on the specific group structure used.

A method is available to remedy this problem. This method redefines the number of photons entering a group by:

$$N^g_{entering} = N^g_{decay} \frac{\bar{E}}{\bar{E}^g} \qquad (1)$$

where N^g_{decay} = number of photons produced in group g per decay of an isotope.

E = energy of the discrete photon entering group g.

$\bar{E}^g$ = median energy of group g.

Use of equation 1 conserves the total source energy independent of group structure, but does not conserve photons. Energy conservation is of most importance in practical problems (dose, photon redistribution heating, and Kerma calculations), and should have been the choice made. This change required alternation of module SDECAY in the BDASS system, and was not made in this testing program because of the relatively small difference (6.9%) between ENDFB022 and ANISN58 source strengths. Future processing of fission product decay spectra by module SDECAY will have this change made so that total photon source energy is preserved independent of group structure.

A part of the answer to the second question of why photon heating was calculated differently by GLASS and SHIELD with one MULTIGRP version was discovered to be different definitions of the γ-heating cross section (σ_γ-heat) and Compton scattering matrix elements ($\sigma_c^{l\to J}$) used in the two modules. GLASS was designed to interface with the ENDFB022 data and SHIELD with the ANISN58 data, and the two sets of cross section data had different fundamental definitions, hence neither module could utilize both sets of data correctly.

The solution to this problem was to establish a consistent definition of the photon interaction cross sections and modify the modules and data to conform to this definition. Because the ANISN58 data was more consistently defined, and because the GLASS module PCRISP was easier to modify the consistent definition of cross section was taken from the data in the ANISN58 version.

III. Definition of Consistent Library Format

The consistently defined photon interaction cross sections in each version of MULTIGRP consist of the following:

$\sigma_T^j \equiv$ total photon interaction cross section in group $j^{(bns)} = \sigma_{cs}^j + \sigma_{ca}^j + \sigma_R^j + \sigma_{PE}^j + \sigma_{PP}^i$, and (2)

$\sigma_{\gamma\text{-heating}}^j \equiv$ γ-heating cross section$^{(ev\text{-}bn)} = (\sigma_{ca}^j + \sigma_{PE}^j)\bar{E}^j + \sigma_{PP}^j(\bar{E}^j - 1.02 \text{ Mev})$, where (3)

$\sigma_{cs}^j \equiv$ Compton scattering fraction cross section$^{(bns)} = \sum_i \sigma_c^{j\to i} \frac{\bar{E}i}{\bar{E}j}$

$\sigma_{ca}^j \equiv$ Compton absorption fraction cross section$^{(bns)} = \sum_i \sigma_c^{j\to i} \frac{\bar{E}^j - \bar{E}^i}{\bar{E}^j}$

$\sigma_R^j \equiv$ Rayleigh scattering cross section (in-group)$^{(bns)}$

$\sigma_{PE}^j \equiv$ Photo electric absorption cross section$^{(bns)}$

$\sigma_{PP}^j \equiv$ Pair production cross section$^{(bns)}$

$\sigma^{i\to j} \equiv$ Compton scattering elements from group i to group j (bns).

The consistently defined transfer matrix element to group j is the following:

$$\sigma^{i\to j} \equiv \sigma_c^{i\to j} + \sigma_R^i \delta_{ij} + 2\sigma_{PP}^i \delta_{jk} \quad (4)$$

where all terms have been previously defined except

$\delta_{ij} \equiv$ Kronecker delta function

$\delta_{jk} \equiv$ Kronecker delta function and k is the energy group containing 0.51 Mev.

The data in MULTIGRP version ANISN58 conformed to the definitions in equations 2, 3, and 4. Module SNONE in SHIELD expected data in this format. In use problems arose because:

- Version ENDFB022 data did not contain the third term in equations (3) and (4), hence errors arose in the SNONE calculation.

- GLASS contained an explicit calculation of the pair production reaction, hence did not require the third term of equations 3 or 4 to be present. When using ANISN58 data pair production was included twice as a result. A module PHMAKE was written that converted ENDFB022 data to be consistent with the definitions in equations 2, 3, & 4. A new version of GLASS module PCRISP was prepared to accept data defined by equations 2 - 4 and remove terms not required in the GLASS calculation. These two modules brought about consistency in library definitions in ENDFB022 and ANISN58 versions of the MUTLIGRP data set, and in usage by GLASS and SHIELD system modules.

  The Mark 42 problem was rerun with the consistent libraries and calculational modules. These problems yielded the results shown in Table II. In these results energy is very nearly conserved by both calculations for both sets of data, and total photon heating is equal for one set of data, but the distribution of heat in the assembly showed large differences. Clearly one of the calculations was in error; however, at the time it was not clear which one.

IV. Tests of Transport Theory Methods

To test the GLASS and SNONE photon transport calculations a simple problem was needed that could isolate different parts of the calculation to identify potential sources of error. The problem used for this purpose is shown in Figure 1 and has only three materials in three geometric zones.

First, MULTIGRP cross sections in a one energy group model were defined for each region. ROD region cross sections were chosen to represent a MARK 16 fuel tube, SPACE region cross sections were chosen to represent water, and RING region cross sections were chosen to represent a heavy pure absorber. Three sets of cross sections were defined corresponding to energies of approximately 4 Mev., 0.75 Mev., and 0.25 Mev.

Comparison calculations were run for each set of one group cross section using GLASS and SHIELD module SNONE. A source of 1 neutron in the ROD region was used in these calculations. Results are shown in Table III and demonstrate good agreement between the calculational methods.

MULTIGRP cross sections were then prepared for each region in the test problem using a two energy group model. Group 1 of these cross sections contained no in-group scattering so that any scattering event removed the photon to group 2. Group 1 fluxes could then be compared to an analytical expression for the uncollided flux given by Rockwell.[6] This analytical expression is reproduced in Figure 2 for reference.

Comparison calculations of GLASS and SHIELD module SNONE were made for the two group cross sections in the geometry of Figure 1. The source for this calculation was one photon in group 1 in the ROD region. Results of these calculations are shown in Table IV and demonstrate large disagreements in results. Comparison of S_n fluxes calculated by module SNONE to the Rockwell analytical fluxes is shown in Table V and demonstrates good agreement.

The results in Table IV along with the results of the 1 group problems indicated a problem in the downscatter model which was ultimately traced to GLASS modules.

V. Errors in GLASS Modules

Several fundamental coding errors were discovered and eliminiated in GLASS Modules PCRISP (photon cross section processor) and PFIST (photon fine structure flux calculation). These errors and the corrections made will be itemized here to document the specific changes made.

MODULE PCRISP CHANGES - subroutine LMGPSM in Module PCRISP loads the photon group-to-group transfer matrices, transport-corrects the total cross section, and removes the third term on the right side of equation 4. In doing this, it multiplied each transfer matrix by a factor of $(2\ell + 1)/4\pi$ where ℓ is the Legendre order of the transfer matrix. This factor converted the transfer element from units of barns to units of barns/steradian. Module PFIST used these transfer elements later in the calculation and presume the units were barns.

The factor $(2\ell + 1)/4\pi$ probably was taken from the differential form of the scattering cross section matrix.

$$\frac{d^2\sigma(E^{i\to j}, \mu)}{dEd\mu} = \sum_{\ell=0}^{L} \frac{(2\ell + 1)}{4\pi}\sigma_\ell^{i\to j} P_\ell(\mu) \qquad (5)$$

where $\sigma_\ell^{i\to j}$ is the scattering matrix for Legendre order ℓ stored in the MULTIGRP data set, and $P_\ell(\mu)$ is the Legendre polynomial of order ℓ.

The factor $(2\ell + 1)/4\pi$ was removed from the calculation performed in subroutine LMGPSM in module PCRISP.

MODULE PFIST CHANGES - module PFIST solves the fixed source, multigroup, multiregion matrix transport equation to obtain the fine structure photon flux in a supercell. Multigroup spatial sources are calculated in module PPROD including sources from neutron interaction events, fixed sources (SHIELD system records), or any combination of the two.

An error was found in subroutine ISODAT of module PFIST which locates and stores into arrays the transfer matrix elements and cross sections for a single isotope.

A temporary storage array (TS) in this subroutine was not zeroed properly. In some cases this would lead to transfer matrix elements where none should have existed.

EFFECTS OF PCRISP ERRORS - the removal cross section from group j was calculated from the expression:

$$\sigma_{rem}^{j} = XS(3) = \sum_{k=j}^{N} \sigma_o^{j\to k} - \sigma_o^{j\to j} \qquad (6)$$

where $\sigma^{j\to k}$ is the P_o transfer matrix element from group j to k.

All of the matrix elements in equation 6 had been divided by 4π in module PCRISP hence the units of σ_{rem}^{j} were barns/steradian.

The in-group scattering cross section $\sigma_o^{j\to j}$ was then re-calculated to conform to the transport approximation

$$\sigma_o^{j\to j} = S(j) = \sigma_{tr}^{j} - \sigma_{abs}^{j} - \sigma_{rem}^{j} \quad (7)$$

where

$$\sigma_{abs}^{j} = \sigma_{PE}^{j} + \sigma_{PP}^{j} \quad (8)$$

$$\sigma_{tr}^{j} = \sigma_{T}^{j} - \sum_{k=j}^{N} \sigma_1^{j\to k} \quad (9)$$

where $\sigma_1^{j\to k}$ is the P_1 transfer matrix element from group j to k.

σ_{tr}^{j} was calculated in module PCRISP in subroutine LMGPSM as previously described. Because σ_{rem}^{j} in equation 6 was in units of barns/steradian the in-group scattering term $\sigma_o^{j\to j}$ calculated from equation 7 was much too large.

This shift of scattering cross section with σ_{rem}^{j} too small and $\sigma_o^{j\to j}$ too large had the effect of removing too few photons from the group and increasing the number of in-group scattering events in the group. This resulted in photons being transported by scattering events away from regions where they would normally be absorbed to that region which had the largest absorption cross section where it was preferentially absorbed. This is exactly what is observed in the MK 42 problem results in Table II and the two-group sample problem in Table IV.

After making the corrections to PFIST and PCRISP, the two-group test problem was rerun and gave good agreement with S_n results as shown in Table VI. Region average relative fluxes from the two problems are also shown in this table and show good agreement.

VI. Transport Approximation Errors

Having achieved agreement between calculational methods for the two-group test problem, the MARK 42 problem was recalculated with GLASS yielding the results shown in Table VII. These results show even worse disagreement than Table II results since these results do not even conserve energy.

Dumps of cross sections for material mixtures from module PFIST revealed the source of the problem to be a negative transport cross section for many energy groups. In most groups where the transport cross section was positive the condition existed that

$$\sigma_{tr}^{j} < \sigma_{abs}^{j} \quad (10)$$

which is aphysical.

The negative transport cross sections produced negative fluxes hence negative power contributions to the results in Table VII.

The source of the negative transport cross sections was traced to the transport correction to the total cross section performed in subroutine LMGPSM in module PCRISP. This correction is calculated by equation 9 which is identical to the transport correction used in module FIST for neutron flux calculations.

The rationale for the transport correction in equation 9 is to approximately correct for anisotropic scattering effects in a P_o flux calculation. For many energy groups, equation 9 results in negative microscopic transport cross sections particularly for heavy isotopes. In all cases $\sigma^J_{tr} < 0.2\ \sigma^J_{TOT}$ for all isotopes and groups primarily because the P_1 component of photon scattering is very large (sometimes larger than P_o scattering).

This transport correction problem did not occur prior to the removal of the $(2\ell + 1)/4\pi$ factor from module PCRISP because the $\sigma^{J\to K}_l$ terms in equation 9 were reduced by this factor hence equation 9 resulted in reasonable values of σ^J_{tr}. Without the $(2\ell + 1)/4\pi$ factor equation 9 yields absurd results.

A simple correction of the module PFIST was made by changing subroutine ISODAT to ignore the transport cross section (equation 9) and use the total cross section in its place. This reduced the PFIST calculation to a transport uncorrected P_o flux calculation. The only major change resulted from equation 7 since $\sigma^{J\to J}_o$ already satisfied this equation with $\sigma^J_{tr} = \sigma^J_T$.

The MARK 42 photon redistribution test problem was recalculate by GLASS with the corrected transport cross section. These results are given in Table VIII and show excellent agreement to the $S_{16}P_3$ results of SHIELD module SNONE.

SUMMARY

The changes that were made to GLASS photon flux calculations were the following:

- A consistent format for photon interaction cross section in the MULTIGRP data set was defined. Data in version ENDFB022 was converted to this format definition and data in the ANISN58 version already conformed to this format.

- Module PCRISP in GLASS was altered to read the new format MULTIGRP data and alter it to the needs of the GLASS photon transport calculation.

- Factors of $(2\ell + 1)/4\pi$ were removed from the GLASS photon transfer matrices to correct errors in definition of σ^{j}_{rem} and $\sigma^{j\rightarrow j}_{o}$ arising from the presence of these factors. These changes were made in subroutine LMGPSM in module PCRISP.

- Transport correction of the total cross setion was removed in subroutine ISODAT in module PFIST. This reduces the PFIST photon flux calculation to a P_o flux calculation, but improves agreement between GLASS and SNONE calculations.

No changes were made to the SHIELD system module SNONE. This module had previously been tested against several test problems including:

- Test problems distributed with the DTF-IV[2] code.

- Test problems defined for the ANISN[7] code.

- Cylindrical test problems having analytical solutions.

The SNONE calculation produced reliable and consistent results throughout this work and generated no suspicion of errors in its results.

The removal of the transport correction to the total cross section is certainly not correct for all photon transport problems. It is probably a reasonable approximation for photon transport in a reactor lattice because no extremely heavy shielding materials are present that generate strongly anisotropic scattering sources. Other methods[8] are available for transport correcting the total cross section and should be evaluated for use in the PFIST calculation.

A notice was sent to GLASS users on October 10, 1980 notifying them that changes would be made to the standard GLASS calculations to implement the correction in this work. The new PCRISP and PFIST modules were installed in the standard GLASS photon transport calculation on October 27, 1980. The consistently defined set of version ENDFB022 MULTIGRP photon interaction cross section was installed in the standard MULTIGRP data set at the same time.

DRF:trm

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TABLE I

MARK 42 Photon Redistribution Heating in Air

(absorber ring boundary conditions - 120 hrs after P11.4 shutdown)

units are watts/ft

	Version ENDFB022 Data			Version ANISN58 Data		
Regions in cell	GLASS	S_{16} P_1	S_{16} P_3	GLASS	S_{16} P_1	S_{16} P_3
Inner Target	1.4	11.9	12.0	16.8	13.5	13.5
Inner Fuel	31.1	59.3	59.8	68.3	62.1	62.7
Middle Fuel	55.8	92.6	93.2	103.3	96.1	96.6
Outer Fuel	35.7	63.9	64.3	72.5	66.6	66.8
Outer Housing	1.2	9.4	9.5	13.8	11.4	11.6
Absorber Ring	736.8	573.0	565.0	1306.0	675.5	675.0
All Air Regions	0.6	0.9	0.7	1.1	1.0	0.6
Total Heat	862.9	811.0	802.5	1581.8	926.5	926.8
Total Source		862.9			926.5	

TABLE II

MARK 42 PHOTON REDISTRIBUTION HEATING IN AIR

(absorber ring boundary conditions - 120 hrs. after P11.4 shutdown)
Units are watts/ft.

	Revised Version ENDFB022 Data		Version ANISN58 Data	
Region in Cell	GLASS*	SNONE ($S_{16}P_3$)	GLASS*	SNONE ($S_{16}P_3$)
Inner Target	1.4	11.9	1.8	13.5
Inner Fuel	31.6	60.0	30.8	62.7
Middle Fuel	56.1	95.3	54.1	96.6
Outer Fuel	35.8	65.4	34.8	66.8
Outer Housing	1.1	9.4	1.4	11.6
Absorber Ring	734.9	617.6	806.2	675.0
All Air Regions	0.1	0.9	0.2	1.2
Total Absorbed Power	861.0	861.5	929.3	918.2
Total Source Power	862.9		926.5	

*GLASS calculation with modified PCRISP module.

TABLE III

RESULTS OF ONE GROUP TEST PROBLEMS

4.0 MeV Cross Sections

Region	Source	GLASS Absorption	Sn Absorption	Ratio GLASS/Sn
Rod	1.0	0.025011	0.024140	1.0361
Space	0.0	0.46256	0.46918	0.98589
Ring	0.0	0.512422	0.50667	1.01135
TOTAL	1.0	1.00000	0.99999	

0.7 MeV Cross Sections

Region	Source	GLASS Absorption	Sn Absorption	Ratio GLASS/Sn
Rod	1.0	0.038106	0.039287	0.96991
Space	0.0	0.0	0.0	-------
Ring	0.0	0.961814	0.96043	1.0014
TOTAL	1.0	1.00000	0.99972	

0.225 MeV Cross Sections

Region	Source	GLASS Absorption	Sn Absorption	Ratio GLASS/Sn
Rod	1.0	0.448619	0.46346	0.96798
Space	0.0	0.123623	0.14280	0.86571
Ring	0.0	0.427755	0.39338	1.08738
TOTAL	1.0	0.99998	0.99964	

TABLE IV

RESULTS OF 2 GROUP TEST PROBLEM

Groups 1 & 2

Region	Source	Glass Absorption	Sn Absorption	Ratio Glass/Sn
Rod	1.0	0.094753	0.21652	0.438
Space	0.0	0.16101	0.19940	0.807
Ring	0.0	0.74388	0.58343	1.275
TOTAL	1.0	0.9964	0.99935	

TABLE V

COMPARISON OF Sn FLUXES TO ANALYTICAL FLUXES

Radius (from Center of Rod)	Sn Flux	Analytical Flux
51.0 cm	2.579×10^{-5}	2.422×10^{-5}
95.5 cm	2.219×10^{-7}	2.011×10^{-7}
98.5 cm	1.220×10^{-7}	8.765×10^{-8}

TABLE VI

RESULTS OF 2 GROUP TEST PROBLEM AFTER CORRECTIONS

Absorptions
(Groups 1 & 2)

Region	Source	GLASS Absorption	Sn Absorption	Ratio GLASS/Sn
Rod	1.0	0.20157	0.21652	0.931
Space	0.0	0.17374	0.19940	0.871
Ring	0.0	0.62469	0.58408	1.070
TOTAL	1.0	1.00000	1.00000	

Region Average Relative Flux Values

	GLASS		Sn	
Region	Group 1	Group 2	Group 1	Group 2
Rod	1.04718	0.44109	1.02626	0.47936
Space	9.3626	694.94	19.41479	797.59
Ring	0.0	6.247×10^{-2}	6.1858×10^{-6}	5.8337×10^{-2}

TABLE VII

MARK 42 PHOTON REDISTRIBUTION POWER

(Absorber ring boundary condition - 120 hrs. after shutdown of P11.4)
(Revised version ENDFB022 cross sections)
Units are watts/ft.

REGION	GLASS*	SNONE ($S_{16}P_3$)
Inner Target	1.3	11.9
Inner Fuel	24.0	60.0
Middle Fuel	36.5	95.3
Outer Fuel	21.3	65.4
Outer Housing	1.6	9.4
Absorber Ring	499.7	617.6
All Air Regions	-7.6	0.9
Total Absorber Power	576.8	861.5
Total Source Power	862.9	

*With corrections to module PCRISP.

TABLE VIII

MARK 42 PHOTON REDISTRIBUTION POWER

(Absorber ring boundary conditions - 120 hrs. after shudown of P11.4)
(Revised version ENDFB022 Data)
Units are watts/ft.

Region	GLASS*	SNONE ($S_{16}P_3$)
Inner Target	12.4	11.9
Inner Fuel	64.4	60.0
Middle Fuel	99.5	95.3
Outer Fuel	67.6	65.4
Outer Housing	10.1	9.4
Absorber Ring	606.5	617.6
All Air Regions	1.0	0.9
Total Absorbed Power	861.5	861.5
Total Source Power	862.9	

*With correction to modules PCRISP and PFIST.

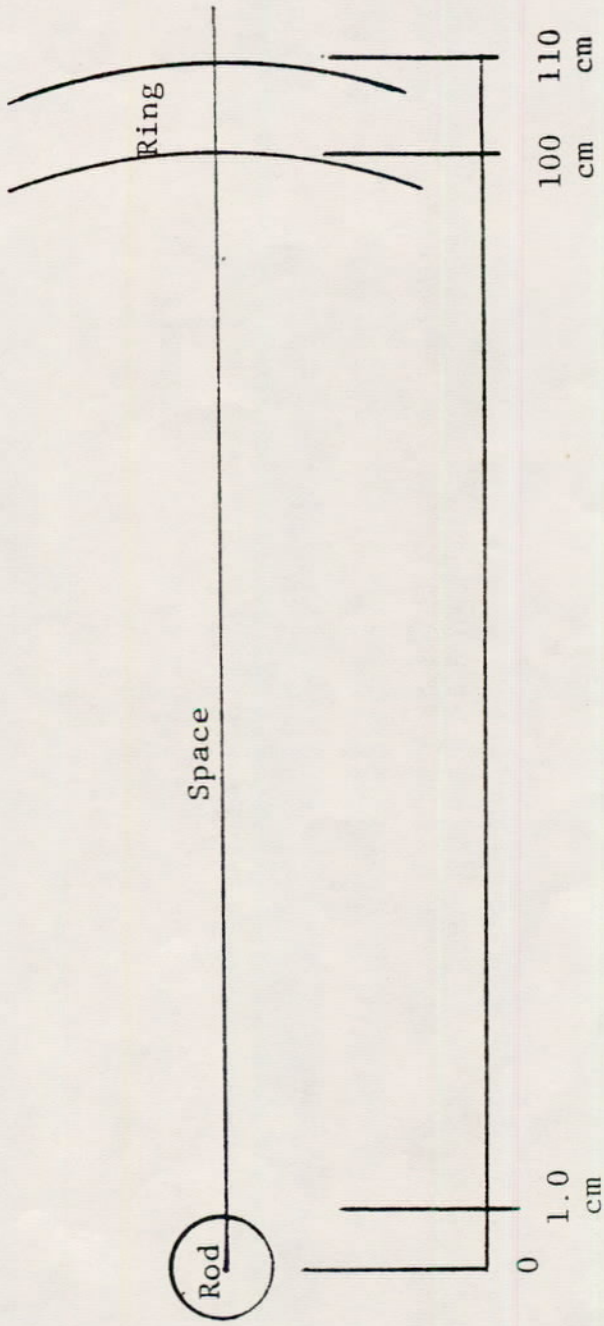


Figure 1

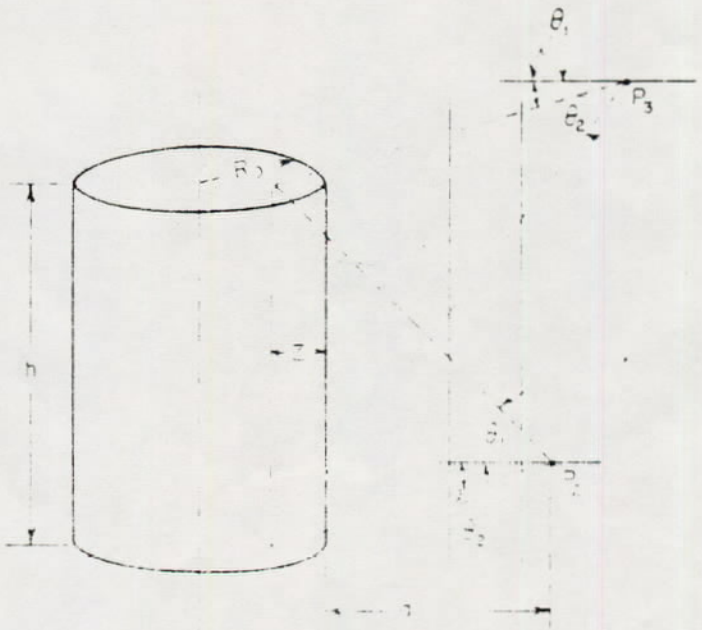
Simple Cylindrical Geometry Test Problem

FIGURE 2

Rockwell Analytical Uncollided Flux Solution

I-6 CYLINDRICAL SOURCE

I-6.1 Exterior on Side (ϕ, Z Curves



At P_2

$$\phi = \frac{BS_V R_0^2}{4(a+z)} \left[F(\theta_1, b_2) + F(\theta_2, b_1) \right] \quad \theta_1 \neq \theta_2$$

At P_2

$$\phi = \frac{BS_V R_0^2}{2(a+z)} F(\theta_1, b_2) \quad \theta_1 = \theta_2 = \pi \quad \text{if } h \ll z, \ \theta = \pi/2$$

At P_3

$$\phi = \frac{BS_V R_0^2}{4(a+z)} \left[F(\theta_2, b_2) - F(\theta_1, b_1) \right]$$

TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

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ERRORS IN GLASS PHOTON TRANSPORT CALCULATION

INTRODUCTION

A calculational capability for photon sources and photon transport in a reactor lattice was added to the GLASS[1] system in 1973. The calculation has been used in a variety of applications since 1973, and has always produced results that appear reasonable. The GLASS photon transport calculation, however, was never compared to an independent photon transport calculation at any state of its development. Recently, the GLASS calculation was compared to calculations performed by the SHIELD system module SNONE (SHIELD system version of LASL DTF-IV[2] code) and significant differences were found in the calculation of deposited photon heat. This led to discovery of certain errors in the GLASS calculations, as discussed in this report.

SUMMARY

Errors were discovered in the GLASS photon transport calculation which can account for as much as a 100% error in redistributed photon heat in a reactor lattice calculation. These errors were discovered while comparing GLASS calculations of the MARK 42 assembly (120 hrs. after reactor shutdown) to SHIELD[3] system calculations with module SNONE for geometries that can be well represented by both calculations. These comparisons are shown in Table I.

The errors in the GLASS calculations were traced to modules PCRISP (Photon Cross Section Processor Module) and PFIST (Photon Fine Structure Flux Calculation). The errors were corrected by reducing the PFIST calculation to the P_o scattering approximation which is adequate for most reactor lattice photon redistribution calculations, and by correcting errors in constants in the PCRISP module. These new modules were installed into the standard GLASS calculation on October 27, 1980 after notifying users of these changes on October 10, 1980.

The effects of the GLASS errors on US2 shutdown heating were evaluated[4] and found to have no impact on charge operation.

DISCUSSION

In February, 1979 an addition was made to the GLASS photon transport calculation that permitted it to read fixed photon sources from SHIELD system records. This was a temporary arrangement to permit use of GLASS to calculate photon redistribution heating using SHIELD system photon sources because SHIELD system S_n transport modules were not available at that time to perform the calculation. The combination of SHIELD system sources and GLASS photon transport were utilized to calculate redistributed photon heating after shutdown for both US1 and US2 assemblies.

In June, 1980 the SHIELD system S_n transport module SNONE (based on the LASL DTF-IV code) had been checked out and could perform photon redistribution calculations with the same sources and cross sections as the GLASS calculation. The GLASS photon calculation, in addition, had several mathematical assumptions that needed checking while the S_n modules treated these same assumptions more rigorously. These GLASS assumptions were:

- Anisotropic scattering represented by a transport corrected P_o calculation.
- Use of cosine current methods for flux and current continuity at zone boundaries in and between lattice cells.

I. Test Comparisons between GLASS and SHIELD

A test problem to compare the two calculations was supplied by J. L. Jarriel and consisted of a MARK 42 assembly in air 120 hrs. after shutdown of the P11.4 subcycle. In these calculations the boundary conditions (in GLASS and SHIELD) were provided by a heavy absorber ring (pure uranium) at a distance of 30 cm from the center of the assembly. This geometry could be represented well by both calculations.

Two sets of photon interaction cross sections were available for use in these calculations, and both sets were used. These cross section sets are the following:

- MULTIGRP photon version ENDFB022 - cross sections processed in 1974 from ENDF/B-IV by the JOSHUA Basic Data Analysis Subsystem (BDASS).[1] The data is in 22 energy groups based from a group structure recommended by the CSEWG Shielding Subcommittee.

- MULTIGRP photon version ANISN58 - cross sections from the Defense Nuclear Agency (DNA) standard library[5] processed from ENDF/B-IV by ORNL. The data has 21 photon energy groups chosen to represent DNA reactor shielding requirements.

The results of these calculations are shown in Table I. The conclusions drawn from these calculations were the following:

- GLASS acieves energy balance with ENDFB022 data - SNONE does not.

- SNONE achieves energy balance with ANISN58 data - GLASS does not.

- A difference of total photon energy exists for the two versions of data. ENDFB022 data shows 6.9% less total photon energy than ANISN58 data.

- SNONE calculated photon heating in the MARK 42 fuel tubes is 80% higher than GLASS with ENDFB022 data.

- SNONE calculated photon heating in the MARK 42 fuel tubes is 5% lower than GLASS with ANISN58 data.

- Angular anisotropy is not important since essentially no difference is seen in P_1 and P_3 calculations with SNONE.

A minor modification was made in GLASS Module PPROD to permit it to utilize the ANISN58 data in the above calculations. Photon production data (from neutron interactions) is loaded irrespective of whether a neutron transport calculation is performed or not. Module PPROD did not recognize production matrix type 'TOTAL' which contains this data in the ANISN58 data. This was a very ninor modification and was implemented without problem or interference to any user.

Two basic questions arose from the results in Table I:

1. Why is there a difference in total source energy for the two MULTIGRP versions?

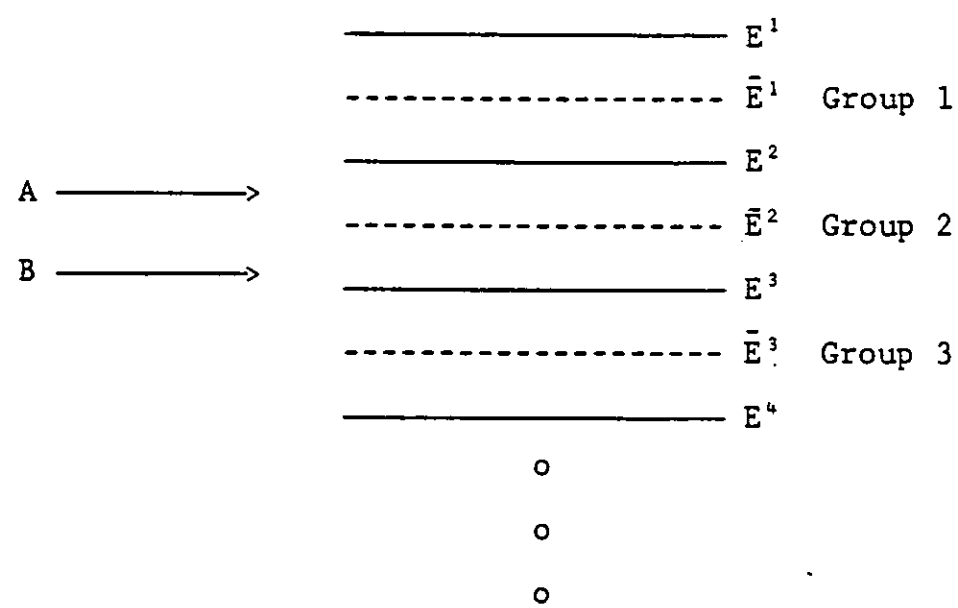
2. Why is there a difference in photon heating results for one MULTIGRP version?

II. Library Data Inconsistencies

The first question was answered by considering the SHIELD system calculation of photon sources. In this calculation discrete photons emitted by many fission products are summed in multi-group form to create an aggregate material photon source. The multigroup spectrum for each fission product was formed by considering each multigroup as a bin and by assigning each photon of energy E such that

$$E_l^g < E \leq E_h^g$$ (E_h^g and E_l^g the high and low energies of multigroup g)

to the g^{th} group. In use, however, all photons in a group are considered to have the average energy ($\bar{E}^g$) of the group. This is illustrated in the following diagram.



A discrete photon can enter the group above or below the median group energy as in A or B above. All photons in a group are assumed to have an average energy of $\bar{E}^g$. If many decays and fission products are summed, the average discrete photon energy in a group will be very nearly $\bar{E}^g$. However, at long times after shutdown only a few fission products contribute to each group. Hence a definite bias above or below the median energy and a shift of apparent total source energy can occur depending on the specific group structure used.

A method is available to remedy this problem. This method redefines the number of photons entering a group by:

$$N^g_{entering} = N^g_{decay} \frac{\bar{E}}{\bar{E}^g} \qquad (1)$$

where N^g_{decay} = number of photons produced in group g per decay of an isotope.

E = energy of the discrete photon entering group g.

$\bar{E}^g$ = median energy of group g.

Use of equation 1 conserves the total source energy independent of group structure, but does not conserve photons. Energy conservation is of most importance in practical problems (dose, photon redistribution heating, and Kerma calculations), and should have been the choice made. This change required alternation of module SDECAY in the BDASS system, and was not made in this testing program because of the relatively small difference (6.9%) between ENDFB022 and ANISN58 source strengths. Future processing of fission product decay spectra by module SDECAY will have this change made so that total photon source energy is preserved independent of group structure.

A part of the answer to the second question of why photon heating was calculated differently by GLASS and SHIELD with one MULTIGRP version was discovered to be different definitions of the γ-heating cross section (σ_γ-heat) and Compton scattering matrix elements ($\sigma_C^{i\rightarrow j}$) used in the two modules. GLASS was designed to interface with the ENDFB022 data and SHIELD with the ANISN58 data, and the two sets of cross section data had different fundamental definitions, hence neither module could utilize both sets of data correctly.

The solution to this problem was to establish a consistent definition of the photon interaction cross sections and modify the modules and data to conform to this definition. Because the ANISN58 data was more consistently defined, and because the GLASS module PCRISP was easier to modify the consistent definition of cross section was taken from the data in the ANISN58 version.

III. Definition of Consistent Library Format

The consistently defined photon interaction cross sections in each version of MULTIGRP consist of the following:

$\sigma_T^j \equiv$ total photon interaction cross section in group $j^{(bns)} = \sigma_{cs}^j + \sigma_{ca}^j + \sigma_R^j + \sigma_{PE}^j + \sigma_{PP}^i$, and (2)

$\sigma_{\gamma\text{-heating}}^j \equiv$ γ-heating cross section$^{(ev\text{-}bn)} = (\sigma_{ca}^j + \sigma_{PE}^j)\bar{E}^j + \sigma_{PP}^j(\bar{E}^j - 1.02 \text{ Mev})$, where (3)

$\sigma_{cs}^j \equiv$ Compton scattering fraction cross section$^{(bns)} = \sum_i \sigma_c^{j\to i} \frac{\bar{E}i}{\bar{E}j}$

$\sigma_{ca}^j \equiv$ Compton absorption fraction cross section$^{(bns)} = \sum_i \sigma_c^{j\to i} \frac{\bar{E}^j - \bar{E}^i}{\bar{E}^j}$

$\sigma_R^j \equiv$ Rayleigh scattering cross section (in-group)$^{(bns)}$

$\sigma_{PE}^j \equiv$ Photo electric absorption cross section$^{(bns)}$

$\sigma_{PP}^j \equiv$ Pair production cross section$^{(bns)}$

$\sigma^{i\to j} \equiv$ Compton scattering elements from group i to group j (bns).

The consistently defined transfer matrix element to group j is the following:

$$\sigma^{i\to j} \equiv \sigma_c^{i\to j} + \sigma_R^i \delta_{ij} + 2\sigma_{PP}^i \delta_{jk} \quad (4)$$

where all terms have been previously defined except

$\delta_{ij} \equiv$ Kronecker delta function

$\delta_{jk} \equiv$ Kronecker delta function and k is the energy group containing 0.51 Mev.

The data in MULTIGRP version ANISN58 conformed to the definitions in equations 2, 3, and 4. Module SNONE in SHIELD expected data in this format. In use problems arose because:

- Version ENDFB022 data did not contain the third term in equations (3) and (4), hence errors arose in the SNONE calculation.

- GLASS contained an explicit calculation of the pair production reaction, hence did not require the third term of equations 3 or 4 to be present. When using ANISN58 data pair production was included twice as a result. A module PHMAKE was written that converted ENDFB022 data to be consistent with the definitions in equations 2, 3, & 4. A new version of GLASS module PCRISP was prepared to accept data defined by equations 2 - 4 and remove terms not required in the GLASS calculation. These two modules brought about consistency in library definitions in ENDFB022 and ANISN58 versions of the MUTLIGRP data set, and in usage by GLASS and SHIELD system modules.

  The Mark 42 problem was rerun with the consistent libraries and calculational modules. These problems yielded the results shown in Table II. In these results energy is very nearly conserved by both calculations for both sets of data, and total photon heating is equal for one set of data, but the distribution of heat in the assembly showed large differences. Clearly one of the calculations was in error; however, at the time it was not clear which one.

IV. Tests of Transport Theory Methods

To test the GLASS and SNONE photon transport calculations a simple problem was needed that could isolate different parts of the calculation to identify potential sources of error. The problem used for this purpose is shown in Figure 1 and has only three materials in three geometric zones.

First, MULTIGRP cross sections in a one energy group model were defined for each region. ROD region cross sections were chosen to represent a MARK 16 fuel tube, SPACE region cross sections were chosen to represent water, and RING region cross sections were chosen to represent a heavy pure absorber. Three sets of cross sections were defined corresponding to energies of approximately 4 Mev., 0.75 Mev., and 0.25 Mev.

Comparison calculations were run for each set of one group cross section using GLASS and SHIELD module SNONE. A source of 1 neutron in the ROD region was used in these calculations. Results are shown in Table III and demonstrate good agreement between the calculational methods.

MULTIGRP cross sections were then prepared for each region in the test problem using a two energy group model. Group 1 of these cross sections contained no in-group scattering so that any scattering event removed the photon to group 2. Group 1 fluxes could then be compared to an analytical expression for the uncollided flux given by Rockwell.[6] This analytical expression is reproduced in Figure 2 for reference.

Comparison calculations of GLASS and SHIELD module SNONE were made for the two group cross sections in the geometry of Figure 1. The source for this calculation was one photon in group 1 in the ROD region. Results of these calculations are shown in Table IV and demonstrate large disagreements in results. Comparison of S_n fluxes calculated by module SNONE to the Rockwell analytical fluxes is shown in Table V and demonstrates good agreement.

The results in Table IV along with the results of the 1 group problems indicated a problem in the downscatter model which was ultimately traced to GLASS modules.

V. Errors in GLASS Modules

Several fundamental coding errors were discovered and eliminiated in GLASS Modules PCRISP (photon cross section processor) and PFIST (photon fine structure flux calculation). These errors and the corrections made will be itemized here to document the specific changes made.

MODULE PCRISP CHANGES - subroutine LMGPSM in Module PCRISP loads the photon group-to-group transfer matrices, transport-corrects the total cross section, and removes the third term on the right side of equation 4. In doing this, it multiplied each transfer matrix by a factor of $(2\ell + 1)/4\pi$ where ℓ is the Legendre order of the transfer matrix. This factor converted the transfer element from units of barns to units of barns/steradian. Module PFIST used these transfer elements later in the calculation and presume the units were barns.

The factor $(2\ell + 1)/4\pi$ probably was taken from the differential form of the scattering cross section matrix.

$$\frac{d^2\sigma(E^{i\to j}, \mu)}{dEd\mu} = \sum_{\ell=0}^{L} \frac{(2\ell + 1)}{4\pi}\sigma_\ell^{i\to j} P_\ell(\mu) \qquad (5)$$

where $\sigma_\ell^{i\to j}$ is the scattering matrix for Legendre order ℓ stored in the MULTIGRP data set, and $P_\ell(\mu)$ is the Legendre polynomial of order ℓ.

The factor $(2\ell + 1)/4\pi$ was removed from the calculation performed in subroutine LMGPSM in module PCRISP.

MODULE PFIST CHANGES - module PFIST solves the fixed source, multigroup, multiregion matrix transport equation to obtain the fine structure photon flux in a supercell. Multigroup spatial sources are calculated in module PPROD including sources from neutron interaction events, fixed sources (SHIELD system records), or any combination of the two.

An error was found in subroutine ISODAT of module PFIST which locates and stores into arrays the transfer matrix elements and cross sections for a single isotope.

A temporary storage array (TS) in this subroutine was not zeroed properly. In some cases this would lead to transfer matrix elements where none should have existed.

EFFECTS OF PCRISP ERRORS - the removal cross section from group j was calculated from the expression:

$$\sigma_{rem}^{j} = XS(3) = \sum_{k=j}^{N} \sigma_o^{j\to k} - \sigma_o^{j\to j} \qquad (6)$$

where $\sigma^{j\to k}$ is the P_o transfer matrix element from group j to k.

All of the matrix elements in equation 6 had been divided by 4π in module PCRISP hence the units of σ_{rem}^{j} were barns/steradian.

The in-group scattering cross section $\sigma_o^{j\to j}$ was then re-calculated to conform to the transport approximation

$$\sigma_o^{j\to j} = S(j) = \sigma_{tr}^{j} - \sigma_{abs}^{j} - \sigma_{rem}^{j} \quad (7)$$

where

$$\sigma_{abs}^{j} = \sigma_{PE}^{j} + \sigma_{PP}^{j} \quad (8)$$

$$\sigma_{tr}^{j} = \sigma_{T}^{j} - \sum_{k=j}^{N} \sigma_1^{j\to k} \quad (9)$$

where $\sigma_1^{j\to k}$ is the P_1 transfer matrix element from group j to k.

σ_{tr}^{j} was calculated in module PCRISP in subroutine LMGPSM as previously described. Because σ_{rem}^{j} in equation 6 was in units of barns/steradian the in-group scattering term $\sigma_o^{j\to j}$ calculated from equation 7 was much too large.

This shift of scattering cross section with σ_{rem}^{j} too small and $\sigma_o^{j\to j}$ too large had the effect of removing too few photons from the group and increasing the number of in-group scattering events in the group. This resulted in photons being transported by scattering events away from regions where they would normally be absorbed to that region which had the largest absorption cross section where it was preferentially absorbed. This is exactly what is observed in the MK 42 problem results in Table II and the two-group sample problem in Table IV.

After making the corrections to PFIST and PCRISP, the two-group test problem was rerun and gave good agreement with S_n results as shown in Table VI. Region average relative fluxes from the two problems are also shown in this table and show good agreement.

VI. Transport Approximation Errors

Having achieved agreement between calculational methods for the two-group test problem, the MARK 42 problem was recalculated with GLASS yielding the results shown in Table VII. These results show even worse disagreement than Table II results since these results do not even conserve energy.

Dumps of cross sections for material mixtures from module PFIST revealed the source of the problem to be a negative transport cross section for many energy groups. In most groups where the transport cross section was positive the condition existed that

$$\sigma_{tr}^{j} < \sigma_{abs}^{j} \quad (10)$$

which is aphysical.

The negative transport cross sections produced negative fluxes hence negative power contributions to the results in Table VII.

The source of the negative transport cross sections was traced to the transport correction to the total cross section performed in subroutine LMGPSM in module PCRISP. This correction is calculated by equation 9 which is identical to the transport correction used in module FIST for neutron flux calculations.

The rationale for the transport correction in equation 9 is to approximately correct for anisotropic scattering effects in a P_o flux calculation. For many energy groups, equation 9 results in negative microscopic transport cross sections particularly for heavy isotopes. In all cases $\sigma^J_{tr} < 0.2\ ^J_{TOT}$ for all isotopes and groups primarily because the P_1 component of photon scattering is very large (sometimes larger than P_o scattering).

This transport correction problem did not occur prior to the removal of the $(2\ell + 1)/4\pi$ factor from module PCRISP because the $\sigma^{J\to K}$ terms in equation 9 were reduced by this factor hence equation 9 resulted in reasonable values of σ^J_{tr}. Without the $(2\ell + 1)/4\pi$ factor equation 9 yields absurd results.

A simple correction of the module PFIST was made by changing subroutine ISODAT to ignore the transport cross section (equation 9) and use the total cross section in its place. This reduced the PFIST calculation to a transport uncorrected P_o flux calculation. The only major change resulted from equation 7 since $\sigma^{J\to J}_{o}$ already satisfied this equation with $\sigma^J_{tr} = \sigma^J_T$.

The MARK 42 photon redistribution test problem was recalculate by GLASS with the corrected transport cross section. These results are given in Table VIII and show excellent agreement to the $S_{16}P_3$ results of SHIELD module SNONE.

SUMMARY

The changes that were made to GLASS photon flux calculations were the following:

- A consistent format for photon interaction cross section in the MULTIGRP data set was defined. Data in version ENDFB022 was converted to this format definition and data in the ANISN58 version already conformed to this format.

- Module PCRISP in GLASS was altered to read the new format MULTIGRP data and alter it to the needs of the GLASS photon transport calculation.

- Factors of $(2\ell + 1)/4\pi$ were removed from the GLASS photon transfer matrices to correct errors in definition of σ^{j}_{rem} and $\sigma^{j\rightarrow J}_{0}$ arising from the presence of these factors. These changes were made in subroutine LMGPSM in module PCRISP.

- Transport correction of the total cross setion was removed in subroutine ISODAT in module PFIST. This reduces the PFIST photon flux calculation to a P_0 flux calculation, but improves agreement between GLASS and SNONE calculations.

No changes were made to the SHIELD system module SNONE. This module had previously been tested against several test problems including:

- Test problems distributed with the DTF-IV[2] code.

- Test problems defined for the ANISN[7] code.

- Cylindrical test problems having analytical solutions.

The SNONE calculation produced reliable and consistent results throughout this work and generated no suspicion of errors in its results.

The removal of the transport correction to the total cross section is certainly not correct for all photon transport problems. It is probably a reasonable approximation for photon transport in a reactor lattice because no extremely heavy shielding materials are present that generate strongly anisotropic scattering sources. Other methods[8] are available for transport correcting the total cross section and should be evaluated for use in the PFIST calculation.

A notice was sent to GLASS users on October 10, 1980 notifying them that changes would be made to the standard GLASS calculations to implement the correction in this work. The new PCRISP and PFIST modules were installed in the standard GLASS photon transport calculation on October 27, 1980. The consistently defined set of version ENDFB022 MULTIGRP photon interaction cross section was installed in the standard MULTIGRP data set at the same time.

DRF:trm

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TABLE I

MARK 42 Photon Redistribution Heating in Air

(absorber ring boundary conditions - 120 hrs after P11.4 shutdown)

units are watts/ft

	Version ENDFB022 Data			Version ANISN58 Data		
Regions in cell	GLASS	S_{16} P_1	S_{16} P_3	GLASS	S_{16} P_1	S_{16} P_3
Inner Target	1.4	11.9	12.0	16.8	13.5	13.5
Inner Fuel	31.1	59.3	59.8	68.3	62.1	62.7
Middle Fuel	55.8	92.6	93.2	103.3	96.1	96.6
Outer Fuel	35.7	63.9	64.3	72.5	66.6	66.8
Outer Housing	1.2	9.4	9.5	13.8	11.4	11.6
Absorber Ring	736.8	573.0	563.0	1306.0	675.5	675.0
All Air Regions	0.6	0.9	0.7	1.1	1.0	0.6
Total Heat	862.9	811.0	802.5	1581.8	926.5	926.8
Total Source		862.9			926.5	

TABLE II

MARK 42 PHOTON REDISTRIBUTION HEATING IN AIR

(absorber ring boundary conditions - 120 hrs. after P11.4 shutdown)
Units are watts/ft.

	Revised Version ENDFB022 Data		Version ANISN58 Data	
Region in Cell	GLASS*	SNONE ($S_{1-6}P_3$)	GLASS*	SNONE ($S_{16}P_3$)
Inner Target	1.4	11.9	1.8	13.5
Inner Fuel	31.6	60.0	30.8	62.7
Middle Fuel	56.1	95.3	54.1	96.6
Outer Fuel	35.8	65.4	34.8	66.8
Outer Housing	1.1	9.4	1.4	11.6
Absorber Ring	734.9	617.6	806.2	675.0
All Air Regions	0.1	0.9	0.2	1.2
Total Absorbed Power	861.0	861.5	929.3	918.2
Total Source Power	862.9		926.5	

*GLASS calculation with modified PCRISP module.

TABLE III

RESULTS OF ONE GROUP TEST PROBLEMS

4.0 MeV Cross Sections

Region	Source	GLASS Absorption	Sn Absorption	Ratio GLASS/Sn
Rod	1.0	0.025011	0.024140	1.0361
Space	0.0	0.46256	0.46918	0.98589
Ring	0.0	0.512422	0.50667	1.01135
TOTAL	1.0	1.00000	0.99999	

0.7 MeV Cross Sections

Region	Source	GLASS Absorption	Sn Absorption	Ratio GLASS/Sn
Rod	1.0	0.038106	0.039287	0.96991
Space	0.0	0.0	0.0	-------
Ring	0.0	0.961814	0.96043	1.0014
TOTAL	1.0	1.00000	0.99972	

0.225 MeV Cross Sections

Region	Source	GLASS Absorption	Sn Absorption	Ratio GLASS/Sn
Rod	1.0	0.448619	0.46346	0.96798
Space	0.0	0.123623	0.14280	0.86571
Ring	0.0	0.427755	0.39338	1.08738
TOTAL	1.0	0.99998	0.99964	

TABLE IV

RESULTS OF 2 GROUP TEST PROBLEM

Groups 1 & 2

Region	Source	Glass Absorption	Sn Absorption	Ratio Glass/Sn
Rod	1.0	0.094753	0.21652	0.438
Space	0.0	0.16101	0.19940	0.807
Ring	0.0	0.74388	0.58343	1.275
TOTAL	1.0	0.9964	0.99935	

TABLE V

COMPARISON OF Sn FLUXES TO ANALYTICAL FLUXES

Radius (from Center of Rod)	Sn Flux	Analytical Flux
51.0 cm	2.579×10^{-5}	2.422×10^{-5}
95.5 cm	2.219×10^{-7}	2.011×10^{-7}
98.5 cm	1.220×10^{-7}	8.765×10^{-9}

TABLE VI

RESULTS OF 2 GROUP TEST PROBLEM AFTER CORRECTIONS

Absorptions
(Groups 1 & 2)

Region	Source	GLASS Absorption	Sn Absorption	Ratio GLASS/Sn
Rod	1.0	0.20157	0.21652	0.931
Space	0.0	0.17374	0.19940	0.871
Ring	0.0	0.62469	0.58408	1.070
TOTAL	1.0	1.00000	1.00000	

Region Average Relative Flux Values

	GLASS		Sn	
Region	Group 1	Group 2	Group 1	Group 2
Rod	1.04718	0.44109	1.02626	0.47936
Space	9.3626	694.94	19.41479	797.59
Ring	0.0	6.247×10^{-2}	6.1858×10^{-6}	5.8337×10^{-2}

TABLE VII

MARK 42 PHOTON REDISTRIBUTION POWER

(Absorber ring boundary condition - 120 hrs. after shutdown of P11.4)
(Revised version ENDFB022 cross sections)
Units are watts/ft.

REGION	GLASS*	SNONE ($S_{16}P_3$)
Inner Target	1.3	11.9
Inner Fuel	24.0	60.0
Middle Fuel	36.5	95.3
Outer Fuel	21.3	65.4
Outer Housing	1.6	9.4
Absorber Ring	499.7	617.6
All Air Regions	-7.6	0.9
Total Absorber Power	576.8	861.5
Total Source Power	862.9	

*With corrections to module PCRISP.

TABLE VIII

MARK 42 PHOTON REDISTRIBUTION POWER

(Absorber ring boundary conditions - 120 hrs. after shudown of P11.4)
(Revised version ENDFB022 Data)
Units are watts/ft.

Region	GLASS*	SNONE ($S_{16}P_3$)
Inner Target	12.4	11.9
Inner Fuel	64.4	60.0
Middle Fuel	99.5	95.3
Outer Fuel	67.6	65.4
Outer Housing	10.1	9.4
Absorber Ring	606.5	617.6
All Air Regions	1.0	0.9
Total Absorbed Power	861.5	861.5
Total Source Power	862.9	

*With correction to modules PCRISP and PFIST.

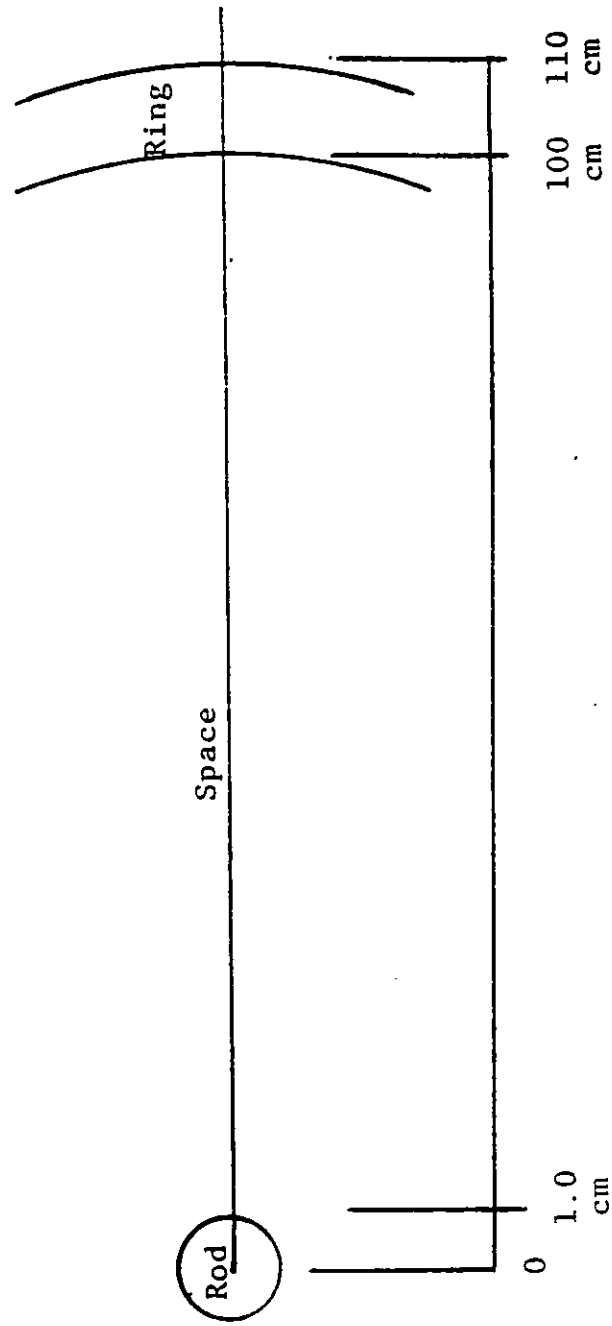


Figure 1

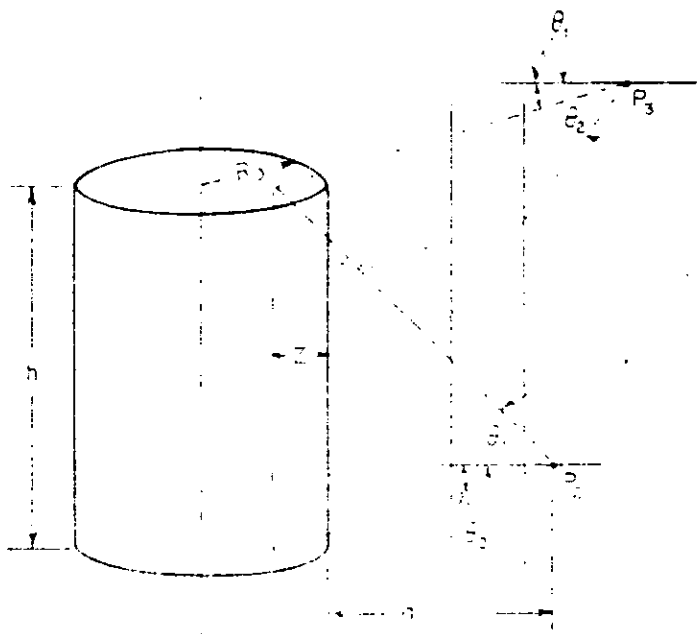
Simple Cylindrical Geometry Test Problem

FIGURE 2

Rockwell Analytical Uncollided Flux Solution

I-6 CYLINDRICAL SOURCE

I-6.1 Exterior or Side (ρ, Z Curves)



At P_2

$$\phi = \frac{BS_V R_0^2}{4(a - z)} \left[F(\theta_1, b_2) + F(\theta_2, b_2) \right] \qquad r_1 \neq r_2$$

At P_2

$$\phi = \frac{BS_V R_0^2}{2(a - z)} F(\theta, b_2) \qquad r_1 = r_2 = r \qquad \text{if } h \quad r, \theta = r \; 2$$

At P_3

$$\phi = \frac{BS_V R_0^2}{4(a - z)} \left[F(\theta_2, b_2) \quad F(\theta_1, b_2) \right]$$