DEVELOPMENT OF POINT KERNEL RADIATION SHIELDING ANALYSIS COMPUTER PROGRAM IMPLEMENTING RECENT NUCLEAR DATA AND GRAPHIC USER INTERFACES

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I. BACKGROUND AND DEVELOPMENT METHOD

There is an increasing demand for safe and efficient use of radiation and radioactive work activity along with shielding analysis as a result the number of nuclear and conventional facilities using radiation or radioisotope rises. Most Korean industries and research institutes including Korea Power Engineering Company (KOPEC) have been using foreign computer programs for radiation shielding analysis. Korean nuclear regulations have introduced new laws regarding the dose limits and radiological guides as prescribed in the ICRP 60. Thus, the radiation facilities should be designed and operated to comply with these new regulations. In addition, the previous point kernel shielding computer code utilizes antiquated nuclear data (mass attenuation coefficient, buildup factor, etc) which were developed in 1950~1960. Subsequently, the various nuclear data such mass attenuation coefficient, buildup factor, etc. have been updated during the past few decades.

KOPEC's strategic directive is to become a self-sufficient and independent nuclear design technology company, thus KOPEC decided to develop a new radiation shielding computer program that included the latest regulatory requirements and updated nuclear data. This new code was designed by KOPEC with developmental cooperation with Hanyang University, Department of Nuclear Engineering. VisualShield is designed with a graphical user interface to allow even users unfamiliar to radiation shielding theory to proficiently prepare input data sets and analyzing output results.

II. FEATURES OF THE PROGRAM

This user-friendly, radiation shielding program, VisualShield, applies the point kernel integration method to estimate dose rates for gamma radiation shielding analysis. This code has various unique distinguishable features when compared against other similar programs and are detailed are below.

1. Point Kernel 15 Fixed Geometry

Radioactive sources and shield structures are fixed in fifteen (15) geometric configurations. Due to the application of the fixed geometric configuration, it is easier to develop the input deck and the possibility of input errors is eliminated when compared to using combinatorial geometry method. Most of radiation shielding problems can be solved within these 15 geometric configurations except for some special cases that require more precise or complex geometry. The available geometric configurations in the VisualShield are shown as follows.

- □ Point Source, Slab Shields
- □ Line source, Slab shields
- □ Sphere source, Sphere shields
- □ Sphere source, Slab shields
- □ Truncated cone source, Slab shields
- □ Disk source, Slab shields
- □ Cylindrical source, Cylinder shields
- □ Cylindrical source, Slab shields
- □ Cylindrical source, Slab shields on cylinder end
- □ Rectangular source, Slab shields
- □ Cylindrical source, Cylinder/Slab shields
- □ Annular/Cylindrical source, Cylinder/Slab shield
- □ Annular source, Slab shields
- □ Annular source in hollow cylinder (outside point)
- □ Annular source in hollow cylinder (inside point)

2. Analysis for 98 Shield Materials and Compounds

Gamma ray attenuation is determined by the mass attenuation coefficient and the density of shield material at a specified photon energy. For an accurate calculation of the attenuation effect of any material, the VisualShield includes attenuation and default density data for material from atomic numbers 1 to 95, with air, water and concrete included. In case of compound materials, the attenuation coefficients are calculated intrinsically using the compound's effective atomic number. These data were obtained from recently published ANSI/ANS 6.4 (1997) and ANSI/ANS 6.4.3 (1991).

3. Application of Geometric Progression (GP) Buildup Factors

Most of the point kernel codes utilize the Taylor-form buildup factor approximation method. VisualShield, however, can use geometric progression (GP) approximation as well as Taylor-form buildup factors. The GP technique closely matches the measured data within the total energy range of gamma rays as shown in section III of this paper when compared to Taylor-form values.

4. Estimation of Effective/Equivalent Dose to 18 Organs from Various Exposure Directions

Dose rates from gamma ray flux are calculated using flux-to-dose conversion factors. In order to apply the dosimetric system of ICRP 60, the VisualShield implements the flux-to-dose conversion factors identified in the ICRP 74 (1997). Equivalent dose rates to 18 organs including effective dose rates are calculated from six (6) different exposure conditions in which radiation field and exposure directions can vary.

Exposure Condition	Organs/Tissue
AP (Anterior-Posterior) PA (Posterior-Anterior) RLAT (Right Lateral) LLAT (Left Lateral) ISO (Isotropic) ROT (Rotational)	Effective, Bladder, Red Bone Marrow, Bone Surface, Breast(Female), Colon, Gonads(Female), Gonads(Male), Gonads(Average), Liver, Lung, Esophagus, Remainder, Skin, Stomach, Thyroid, Eye lens, Thymus, Uterus

Exposure conditions and organs considered in VisualShield are shown above. In addition, exposure rates in units of mR/hr and absorbed dose rate evaluations are shown.

5. Evaluation for 550 Nuclide Decay Data / 0.01~10 MeV Gamma Energy Range

Radiation source can be selected as activity level of radionuclide or photon intensity at a specified energy. VisualShield has an internal library of radioactive decay data for 550 nuclides and gamma ray energies ranging from 0.01 to 10 MeV.

6. Sensitivity Analysis

When calculating required shield thickness to meet the dose rate criteria, other programs perform several calculations by varying shield thickness. To avoid repetitive program runs, VisualShield applies a sensitivity analysis function in which the code generates multiple dose rates as a function of shield thickness automatically. Also, the code determines the thickness that will meet the dose rate criteria that the user wants.

7. Three Dimensional Visualization and Graphic Analysis

When developing input deck data for source/shield configuration, error and error detection are difficult to identify. To reduce these errors and to maximize visual effect, the VisualShield displays the geometric configuration with three-dimensional models. The OpenGL graphic library implemented in theVisualShield code scales the modeled figures from various directions. Models can shrink or grow, change any color or texture appropriate to its material, and even rotate along each axis. Output results such as decay data, attenuation coefficient, density, photon flux, dose rates, sensitivity results, etc., are shown on various graphs for convenient review.

8. Advanced Graphic User Interfaces

All the procedures including input preparation, program running and output data review are processed with graphical user interfaces via Visual Basic programming. Furthermore, error-checking functions at every step eliminates inadvertent errors and error propagation. Numerical processing routine in VisualShield, which is coded with Digital Visual Fortran, is compiled to the dynamic link library without the DOS window during calculation execution.

III. BASIC MODELS AND DATA LIBRARY

This section describes the basic models and data applied in VisualShield and discusses the effects of the new nuclear data by comparing with previous shielding analysis codes.

1. Point Kernel Shielding Analysis Method

Radiation shielding analysis technology can be classified into three different categories. The three categories are the point kernel, discrete ordinate and Monte Carlo methods in an ascending order of complexity or difficulty. Generally, the Monte Carlo method, used in the MCNP code, is utilized for shielding analysis requiring precise estimation in complex geometric configurations, thereby prerequisite knowledge and sufficient time becomes a key factor. ANISN computer code, utilizes the discrete ordinate method, is used for analysis of neutron and secondary gamma transport analysis. Most photon analysis are solved with point kernel method, in which the dose rates from many differential source volumes are summed as total dose rate at the dose point. This method has reasonable accuracy in addition to the merit of its simplicity. Thus, even in the design of nuclear power plant, the point kernel method is most frequently used for gamma ray shielding analysis. The basis of point kernel method begins with the dose rate from a differential source volume as in the following.

$$D_p(E) = \left\{\frac{C(E)S_0(E)}{4\pi V}\right\} \cdot B(E,\mu t)\frac{e^{-b}}{R^2}dV \,, \quad b = \sum_{i=1}^{N} \mu_i t_i$$

where,

$D_p(E)$	: Dose rate from differential source volume[Sv/hr]
$C(E)$	: Flux-to-dose conversion factor [Sv/hr/#/cm^2-sec]
$B(E, \mu t)$	: Buildup factor
$S_o(E)$	: Photon production rate [#/sec]
R	: Distance from source volume to dose point [cm]
μ_i	: Linear attenuation coefficient of ith shield [cm^{-1}]
t_i	: Thickness of ith shield [cm]

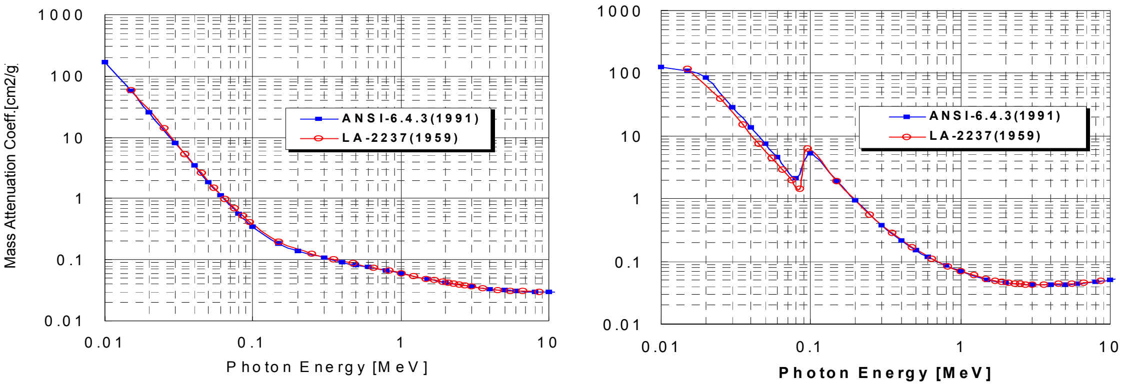
Total dose rate at the dose point is integrated for total photon energy and total source volume.

$$D_V = \int_E \int_V \left\{\frac{C(E)S_0(E)}{4\pi V}\right\} \cdot B(E,\mu t)\frac{e^{-b}}{R^2}dVdE$$

2. Mass Attenuation Coefficients

The attenuation of a parallel beam of photon in a medium is expressed as linear attenuation coefficient μ, which is the probability of interaction in unit distance that can be converted to the mass attenuation coefficients divided by the medium density. While mass attenuation coefficients of previous code such as ISOSHLD adopted those in LA-2237, VisualShield code implements the mass attenuation coefficients in ANSI/ANS 6.4.3. Figure 1 compares the two data sets for iron and lead, which are the major shielding materials for gamma rays.

Even though the values of two data sets seem identical in the log-log graphs, the differences



(a) **(b)**

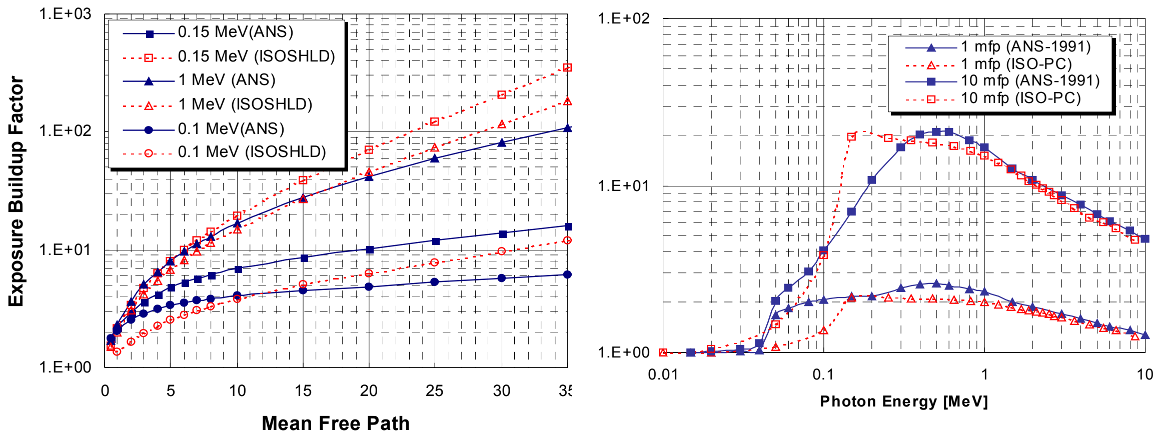
Figure. 1. Mass attenuation coefficients for (a) iron and (b) lead.

are 14.5% and 9% for 0.1 MeV of photon in iron and lead, respectively. For 1.0 MeV photon, they are 0.4% and 2.6% with LA-2237 being the higher. Due to the exponential decreasing characteristics, the dose rate differences are much large in thicker medium; for example, 14.5% of mass attenuation difference results in 5% and 78% differences in dose rates at 1 mfp and 30 mfp, respectively.

3. Buildup Factors

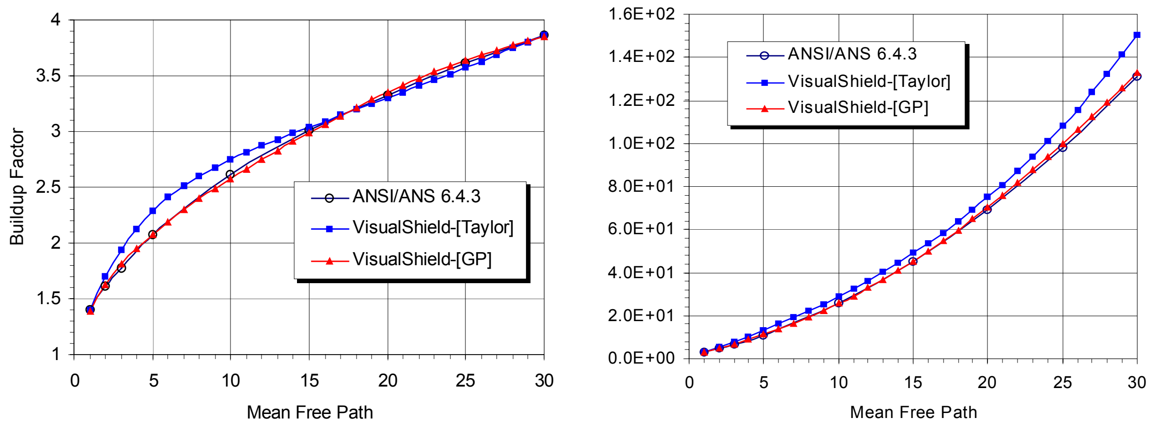
The point kernel method can not evaluate the effect of scattered photon from non-parallel directions. Adjustments are made for this scattered radiation using buildup factors, which is defined as the ratio of total intensity to the uncollided intensity at the dose point. ISOSHLD code utilizes the Taylor-form buildup factors developed by Goldstein in 1959 for 7 materials (Water, Al, Fe, Sn, W, Pb and U), while VisualShield implements the recent ANS buildup factors. These two buildup factors are compared in Figure 2 for iron, and it reveals significant differences in the values. Since the buildup factor is multiplied to the uncollided response, the relative error in dose rates is same as that of buildup factor. VisualShield utilizes two different fitting scheme for the buildup factors: Taylor and GP form. The GP fitting is known as the most accurate form among the several fitting functions.

The comparison of Taylor and GP buildup factors is shown in Figure 3 for iron and concrete at 0.1 MeV. The GP fitting almost identically agrees with the ANSI/ANS 6.4.3 values.



(a) (b)

Figure. 2 Comparison of buildup factors for iron prescribed in ANSI/ANS with those used in ISOSHLD as a function of (a) shield thickness and (b) photon energy.



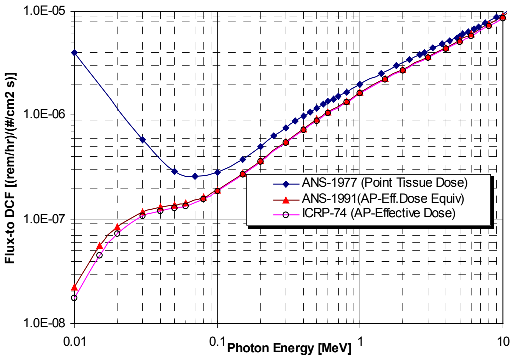
(a) (b)

Figure. 3 Effect of the fitting functions on the buildup factors of 0.1 MeV photons (a) Iron (b) Concrete

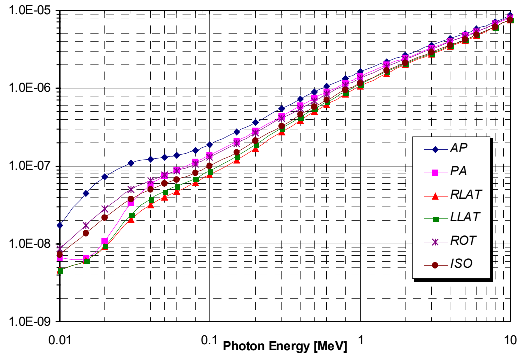
4. Flux-to-Dose Conversion Factors

The dose rate for human being is calculated by multiplying the photon flux by the flux-to-dose conversion factor. Flux-to-dose conversion factors (DCF) have been published in ANSI/ANS 6.1.1 (1977), ICRP 51 and ICRP 74 to accommodate changes in the definition of protection quantity. DCFs in ANSI/ANS 6.1.1(1977) are based on the dose equivalent to a point tissue in free air and DCFs in ICRP 51 are presented in terms of the ambient dose equivalent, organ dose equivalent and effective dose. DCFs in ICRP 74 are based on the same quantities with the slightly higher values due to the changes in tissue weighting factors after ICRP 60. These three data sets are compared in Figure. 4 for various exposure conditions.

In Figure 4 (a), DCFs of ANS-1977 indicated in low energy range are quite higher than that of the new data set. The effects of exposure direction are also larger at low energies and the anteria-to-posteria (AP) exposure indicates higher doses.



(a)



(b)

Figure 4. Comparison of DCFs. (a) Point tissue dose DCF and effective doses, (b) Effect of irradiation direction on DCFs for effective dose, where AP denotes anteria-to-posteria, PA posteria-to-anteria, RLAT right lateral, LLAT left lateral, ROT rotational, and ISO isotropic irradiation conditions.

IV. GRAPHIC USER INTERFACES

One of the merits of VisualShield is that all the calculation procedures are handled on an advanced graphical user interfaces.

1. Input Preparation and 3-D Models

All the data for VisualShield analysis are in a single window for input as shown in Figure 5, and geometric configuration of source and shields are visualized by the OpenGL graphic library.

The main input window is composed of four input forms, 'Geometry', 'Exposure', 'Source' and 'Property', and two graphic forms, 3-D view and result review. Each input form is composed of several tabs.

'Geometry' form has the functions of geometric configuration selection, dimensions, material/density and sensitivity input parameters. The four input forms are saved in a block and the user can create up to 20 blocks. Unit of length can be 'cm', 'feet', or 'inches'. Source and shield materials can be selected from 98 menu materials. When the user selects one of them, nominal density of the selected material is shown in the input table. The automatic mode for sensitivity analysis calculates the number of iteration once the user-specified initial, final and increment thickness.

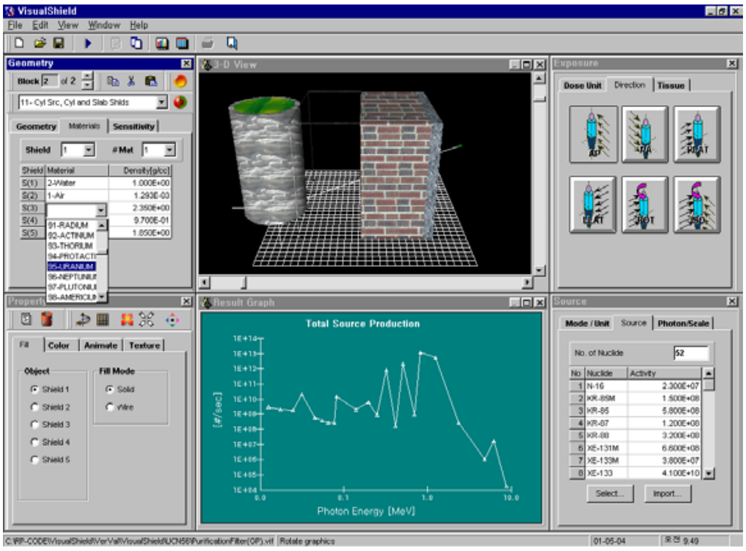


Figure 5. Main input window of VisualShield

Unit of dose rate, exposure direction, and organs are specified in the 'Exposure' form. User can select all the 19 organs at once.

'Source' form has input decks for source activity or strength, source unit, and scale factor for each nuclide. For activity mode, the user can select nuclide from the program or open a existing source data file.

Graphic properties of the 3-D graphic model are determined in the 'Property' form. Color, texture, rotation, fill/wire mode, x-z grid on/off mode, shrink/expand mode and viewing angles can be changed easily. Input data report saved as text file format can also be shown in the '3-D View' window by clicking the report-shaped button.

Since the input data sets are checked at every step, the error message alerts whenever the user makes an inadvertent error.

2. Analyzing Output Results

When the program has been successfully executed, the output results are analyzed graphically on the graph window, which is shown in Figure 6.

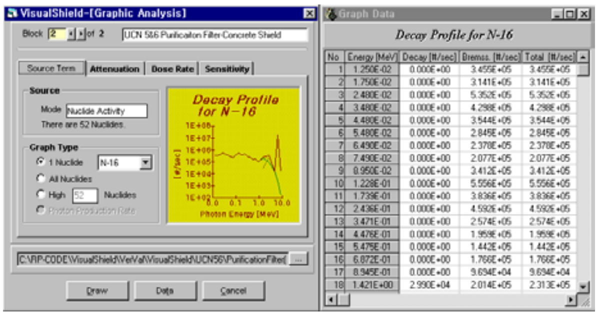


Figure. 6. Result Analysis Window of VisualShield.

The analysis result window is composed of ‘Graph’ and ‘Data’ forms. In the ‘Graph’ form, there are four tabs, ‘Source Term’, ‘Attenuation’, ‘Dose Rate’ and ‘Sensitivity’ for detailed analysis of 10 different graphs.

‘Source Term’ tab generates graphs for decay radiation data of input nuclide including gamma and bremsstrahlung production rates. The user can find most contributing nuclides by selecting the graph type of ‘All Nuclides’.

Attenuation coefficients and densities of shield materials are shown in ‘Attenuation’ tab.

‘Dose Rate’ tab of ‘Graph’ form has graphs for collided flux, exposure/absorbed dose rate and effective/equivalent dose rate as a function of photon energies including energy-total values.

Sensitivity analysis results are drawn in ‘Sensitivity’ tab as a function of shield thickness. If the user wants to determine the thickness of the material at a certain dose rate, VisualShield automatically calculates, and vice versa.

The properties (type, font, color, title, grid, etc.) of the produced graph can be modified in the popup window shown by clicking the right mouse button on the graph. The output file is saved as a text file and can be viewed or printed by the VisualShield’s internal editor.

V. CODE VALIDATION AND SAMPLE CALCULATIONS

Validation of the VisualShield was performed by comparing the calculation results of various analyses with the previous programs. Firstly, for the verification of the calculation logic was validated by comparison the VisualShield outputs with the manual calculations conducted for various materials and thickness at different range of photon energy having a point source configuration. Secondly, the reference problems in ANSI/ANS 6.6.1 were also selected for the purpose of comparison review. Finally, an actual radiation shielding analysis was performed for a nuclear power plant purification filter and the effects of the design application were evaluated.

1. Point Source Problems

Since the point kernel method sums the contribution of each point source, it is said that validation against point source analysis is directly related to the accuracy of the entire program. Many analysis were made for 37GBq (1 Ci) of point sources of photon with energies ranging between 0.1~1 MeV. Shield materials have different thickness from 1~30 mfp for air, water, carbon, aluminum, iron, ordinary concrete, lead and uranium. VisualShield runs were performed with GP buildup factors, and the comparisons were analyzed with the ISOSHLD-II, Microshield 5 and MCNP 4B.

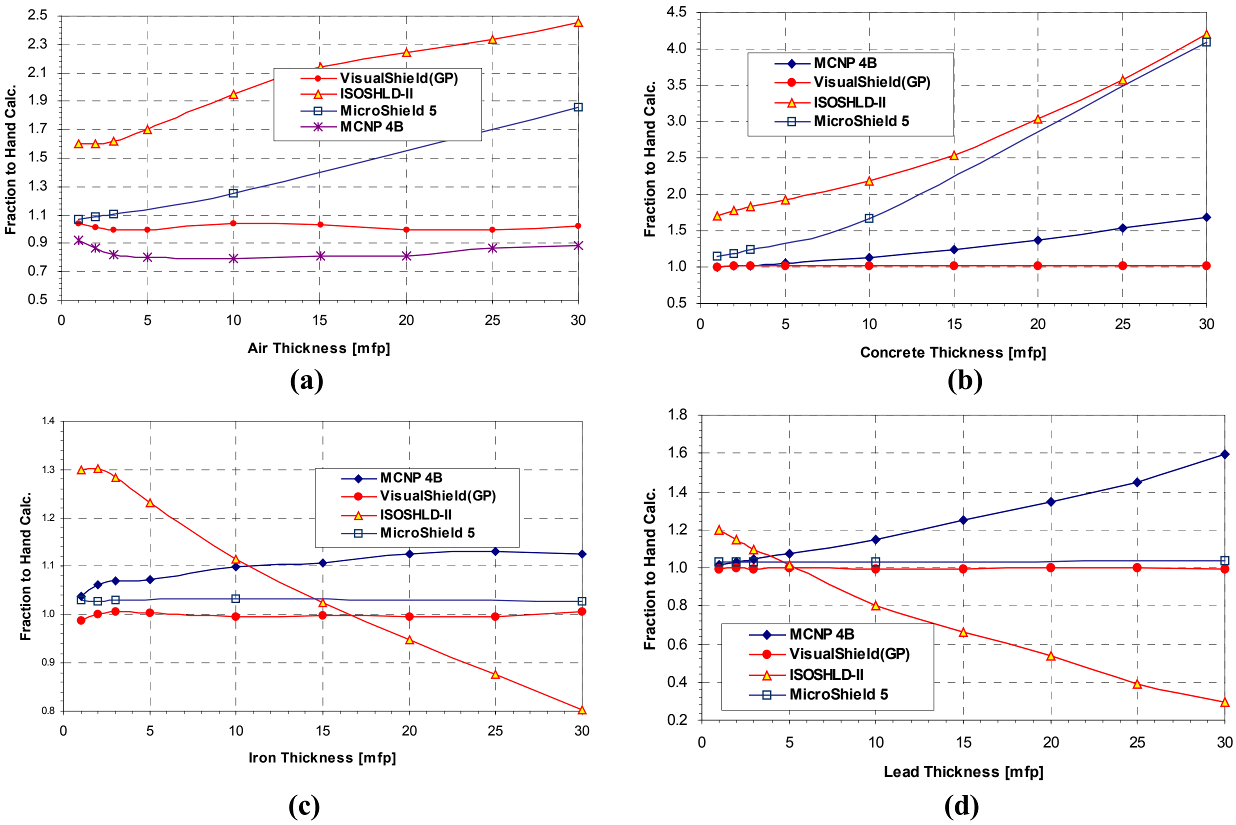


Fig. 7. Comparison of dose rates resulting from a point source of 37GBq calculated with different tools. (a) and (b): air and concrete against 0.1 MeV photons, (c) and (d): iron and lead against 1 MeV photons.

For manual calculations, the mass attenuation coefficients and buildup factors in ANSI/ANS 6.4.3 and DCFs in ICRP 74 were used directly. As shown in Figure. 7, the ratio of VisualShield with GP buildup factors to the manual calculation approaches to unity for all material, thickness and energy.

2. ANSI/ANS 6.6.1 Reference Problems

Guidelines for the shielding analysis using computer program and comparison among many programs are described in ANSI/ANS 6.6.1. The reference problems are two cases for point source and two for cylindrical source geometric configuration. One of each two cases is for air shield and another one is for concrete shield. The dose rate results of the VisualShield and other programs are shown in the Table 1. The results of the analysis indicated that the values are similar to other codes.

Table 1. Comparison of results obtained with different shielding codes for some of the ANSI/ANS 6.6.1 reference problems.

Code	Dose Unit	ANSI/ANS 6.6.1 Reference Problem*			
		I.1	I.2+	II.1	II.2+
VisualShield	[R/yr]	8.883E-11	1.688E-13	3.989E-02	6.631E-06
	[rem/yr]	6.910E-11	1.308E-13	3.357E-02	5.580E-06
ISO-PC 2.1	[R/yr]	8.800E-11	1.235E-13	4.860E-02	4.397E-06
	[rem/yr]	7.385E-11	1.035E-13	4.199E-02	3.799E-06
ISOSHLD-II	[R/yr]	N/A	N/A	N/A	N/A
	[rem/yr]	8.044E-11	3.453E-14	4.484E-02	4.095E-06
MicroShield 5	[R/yr]	8.420E-11	1.666E-13	3.964E-02	6.275E-06
	[rem/yr]	7.083E-11	1.538E-13	3.592E-02	5.685E-06
QAD-CGGP-A	[R/yr]	1.212E-10	N/A	6.873E-02	N/A
	[rad/yr]	1.058E-10	N/A	6.000E-02	N/A
MCNP 4B	[R/yr]	1.108E-10	N/A	3.544E-02	N/A
	[rem/yr]	N/A	N/A	N/A	N/A
Reference Codes	Min [rad/yr]	8.000E-11	N/A	4.000E-02	N/A
	Max [rad/yr]	1.300E-10	N/A	7.000E-02	N/A

*) Problem description
I.1 : N-16 Point source, 1 Bq, Air, Dose point at 200 ft
I.2 : N-16 Point source, 1 Bq, 4 ft Concrete shield, Air, Dose point at 200 ft
II.1 : 0.8 MeV, 30 MeV/cm^3-sec, Cylindrical source, Air, Dose point at 100 ft
II.2 : 0.8 MeV, 30 MeV/cm^3-sec, Cylindrical source, Concrete shield 2 ft, Air, Dose point at 100 ft

+) Since the dose rates for problem I.2 and II.2 are influenced by scattered radiation from the ground, those from unscattered radiation are only considered.

3. Purification Filter Shielding Problem

For the estimation of applicability to actual design, the shielding analysis for purification filter of chemical and volume control system in a nuclear power plant was tested and compared with ISOSHLD-II. ISOSHLD was used for determination of shield thickness for Korean Standard NPPs. Dose rates of VisualShield were calculated using the effective dose DCF for AP exposure direction with GP buildup factors.

Dose rates of VisualShield are generally lower than ISOSHLD-II and the difference becomes greater as the thickness of the concrete increases. If we assume that the design dose rate of the filter room is 1 μSv/hr, then the required thickness of concrete is reduced by 3 inches in contrast with former design values.

VI. CONCLUSIONS

For the purpose of complying with revised regulations, KOPEC developed a new point kernel shielding analysis computer code, named VisualShield, that implements state-of-the art nuclear data and advanced graphic interfaces. Based on nuclear power plant design experience and in cooperation with Hanyang University, the VisualShield was designed, coded and verified. Validation was performed against the ANSI/ANS 6.6.1 reference problems. In addition, the VisualShield utilizes user-friendly graphical interfaces so that users without radiation shielding theory and/or skills in engineering programs can easily and proficiently prepare input data sets and analyze calculated results.
The VisualShield was originally developed for the use in NPP design. However, most of the radiation shielding problems encountered in the field that requires gamma shielding analysis are now expected to be solved with the VisualShield.

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