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Graphical Environmental Pathway Analysis Software TEDII-60 Incorporating ICRP-60 Recommendations

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Abstract

Korean nuclear regulation recently adopted into the law the dose limits and concepts of ICRP-60. The public dose limits applied to the design of nuclear facilities are implemented using the dosimetric system provided in ICRP-60. Therefore, a new offsite dose assessment computer code was developed to prepare the Safety Analysis Reports and Environmental Reports for all new NPPs as well as plants currently operating.

KOPEC (Korea Power Engineering Co, Inc), which is the sole NPP designer in Korea, has developed a new computer code, named TEDII-60 (Totally Visualized Environmental Dose Assessment Code System Incorporating ICRP-60 Recommendations) which ensures compliance with ICRP-60 recommendations. It encompasses all the related processes for the offsite dose analysis such as meteorological raw data processing, atmospheric and oceanographic dispersion analysis, and design phase expected annual effluent release rate analysis using perfect graphic I/O display. Pathway analyses are conducted for a maximum of 27 tissues or organs of 6 age groups for both maximally exposed individual and the population within 80km of the site. This code uses dose coefficients from recent ICRP publications and USEPA reports which include nearly 800 radionuclides. TEDII-60 can assess doses from all the chemical forms and particle sizes from the 0.001~10 :m AMAD of any nuclide.

This code has been verified by the Korean regulatory body and academic institutes and compared with formerly released programs. TEDII-60 will soon be used to perform dose assessment of new Korean NPPs and operating plants once additional administrative procedures are completed.

Introduction

The International Commission on Radiological Protection (ICRP) recommendations influence many countries throughout the world in the application of radiation protection to nuclear power plants, nuclear irradiation facilities, and medical radiological institutes. Publication 60[7] of ICRP consolidates these effects. In the publication, the fundamental dosimetric system of radiation risk to men has been modified based on scientific improvement through epidemiological investigation and experiments. The Korean regulatory body has also made great efforts to accommodate the new ICRP recommendations into the law over the period of 1992 to 1997. Accordingly, Decree No.98-12 was announced by MOST (Ministry of Science and Technology) in 1998 to implement ICRP recommendations[1].

The design and operation phases of nuclear facilities are significantly impacted by the new regulation. One important impact is the conceptual change of public dose limits due to operation of nuclear power plants. The regulations have replaced organ doses with effective / equivalent doses per ICRP-60. In order to cope with these changes, the Radiation Protection Group of the Mechanical System Department at KOPEC set forth to develop a new computer code. The new code, named TEDII-60 (Totally Visualized Environmental Dose Assessment Code System Incorporating ICRP-60 Recommendations), implements ICRP-60 in a user-friendly graphical interface which runs on personnel computers. This paper describes the main technical models and features provided in TEDII-60 as well as validation and application aspects.

Structure and Functions of the Program

Many preliminary processes are needed to evaluate public doses due to gaseous and liquid effluents which are released during normal power operation of the nuclear power plants. TEDII-60 code was developed to encompass all the related processes for offsite dose analysis. Figure 1 shows the schematic diagram of TEDII-60's functional structure.

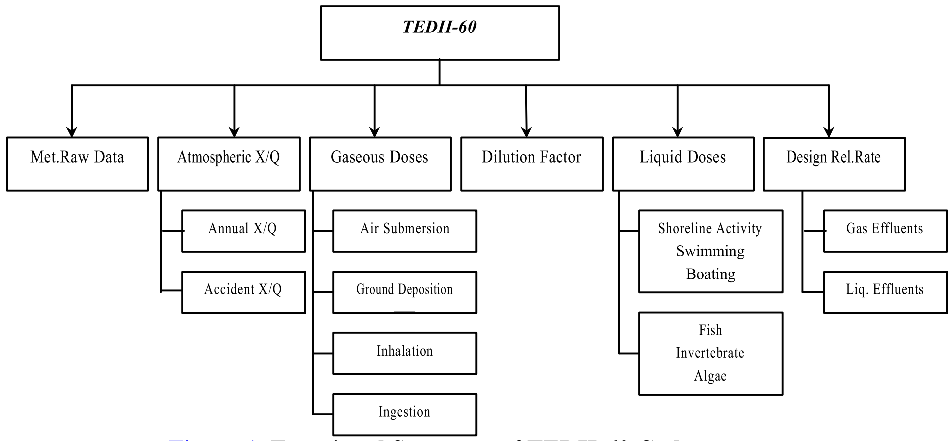

Figure 1. Functional Structure of TEDII-60 Code

Since most of the TEDII-60 functional routines are related to each other, the output result of a routine can be used as input data to another routine. Their functions are described below.

- **Statistical Processing Routine of Meteorological Raw Data**
  This routine generates joint frequency data by statistically processing the meteorological raw data obtained from the meteorological tower. The automatic data acquisition system of the tower generates raw weather data such as wind speed, wind direction, and wind stability, generated every 15 minutes or 1 hour. This routine generates an independent output file separate from the joint frequency data file, and displays the characteristics of the raw data graphically.
- **Design Based Expected Annual Release Rate Assessment Routine**
  This routine is needed for evaluating design based expected release rates of gaseous and liquid effluents. For an operating plant it can be used to predict changes in release rate in response to varying the operation characteristics. The PWR-GALE code[3] is incorporated in this routine. The resultant output is used as input data for the dose analysis routines.
- **Atmospheric/Oceanographic Dispersion Routine**
  The joint frequency data file is input to this routine to calculate annual average and time dependent short-term atmospheric dispersion factors. Oceanographic dilution factors are calculated with five different release modes. Mathematical models of atmospheric dispersion and oceanographic dilution are those provided in USNRC Regulatory Guide 1.111[14] and 1.113[15], respectively.
- **Dose Analysis Routine due to Gaseous Effluents**
  Doses to the maximally exposed individual and population within 80km from the site are evaluated with the joint frequency data and annual gaseous effluent release rate data. External exposure pathways are air submersion in semi-infinite cloud source and ground shine from infinite plane source. Inhalation of contaminated air and ingestion of food are considered for

internal pathways. Calculated doses are effective and equivalent doses defined in ICRP-60. In case of multiple units on a site, realistic geometries are applied i.e., real distance and direction from each unit to the overall site boundary is used to assess maximum individual doses at the site boundary.

- **Dose Analysis Routine due to Liquid Effluents**
  Oceanographic dilution factors and annual liquid effluents release rates are used as input for this routine to calculate maximum individual and population doses to the public from liquid effluents. Exposures from swimming, boating and shoreline activity are considered for external pathways, and ingestion of fish, invertebrate and algae are considered for internal pathway.

Visual Basic (VB) programming language was used for graphical user's I/O interfaces, and Fortran language was used for the mathematical calculations. To enable the exchange of parameters between two computer languages, the Fortran subroutines were compiled using Digital Visual Fortran to create dynamic link library (DLL). This method makes execution of Fortran subroutines invisible without making a DOS window while transferring parameters. The ASCII text format input file created by VB interfaces are used as input parameters to the Fortran DLL subroutines, and then the calculated output file is input to another DLL which then transfers the resultant parameters to VB interfaces. VB interfaces then display the results graphically using these parameters. The programming structure of TEDII-60 is shown in Figure 2.

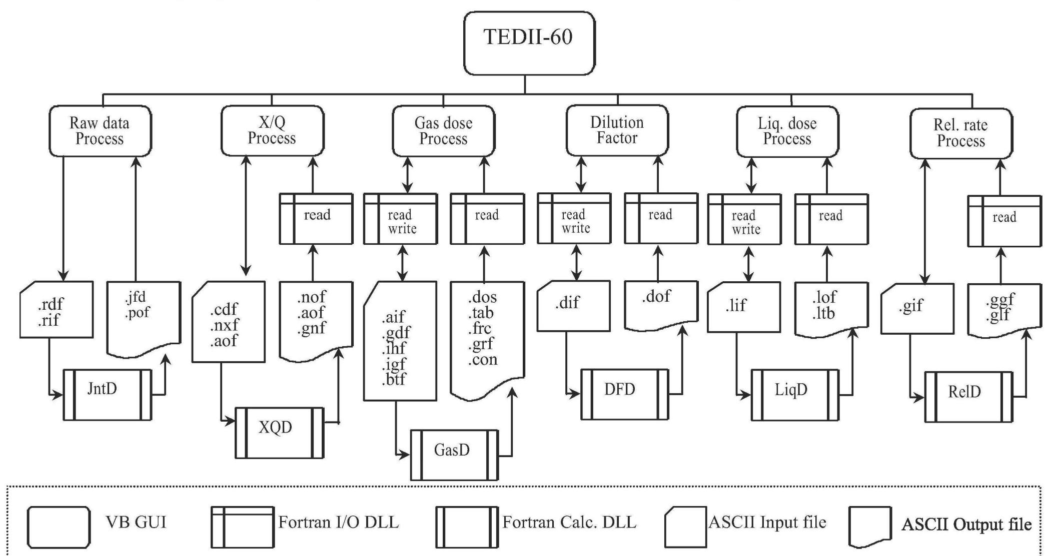

Figure 2. Programming Structure of TEDII-60

Basic Models for Dose Assessment

To estimate the radiation dose due to gaseous and liquid releases from NPPs, assumptions and basic models in USNRC Regulatory Guide 1.109[13] were adopted. However, the model of radioisotope transfer from soil to a plant was modified to incorporate recent studies[20] which separate transfer factors into two types considering dry weight and fresh weight of the plant. The basic equations for dose assessment are described in Table 1 and the input parameters are in Table 2.

Table 1. **Basic Equations Used for Dose Assessment from Gaseous and Liquid Effluents**

Pathways		Equations	No
GASEOUS	Air Gamma Absorbed Dose	$D^{\gamma}(r,\theta) = \sum_i Q_i\,[\chi/Q]^D(r,\theta)\,DF_I^{\gamma}$	(1)
	Air Beta Absorbed Dose	$D^{\beta}(r,\theta) = \sum_i Q_i\,[\chi/Q]^D(r,\theta)\,DF_I^{\beta}$	(2)
	Air Submersion	$H_T^{\infty}(r,\theta) = S_F \sum_i \chi_i(r,\theta)\,DCF_{T,i}^{\infty}$	(3)
	Ground Deposition	$H_T^{G}(r,\theta) = S_F \sum_i C_i^G(r,\theta)\,DCF_{T,i}^{G}$	(4)
	Inhalation	$H_{T,a}^{A}(r,\theta) = R_a \sum_i \chi_i(r,\theta)\,DCF_{T,a,i}^{A}$	(5)
	Ingestion	$H_{T,a}^{I}(r,\theta) = \sum_i DCF_{T,a,i}^{I}\,[U_a^v f_g C_i^v(r,\theta) + U_a^m C_i^m(r,\theta) + U_a^F C_i^F(r,\theta) + U_a^L C_i^L(r,\theta)$	(6)
LIQUID	Ingestion	$H^I{}_{T,a} = 1.119\times10^6 \dfrac{U^W{}_a M_p}{F} \sum_i Q_i B_{ip} DCF^I{}_{T,a,i} \exp(-\lambda_i t_p)$	(7)
	Shoreline Activity	$H^S{}_{T,a} = 0.26 \dfrac{U^W{}_a M_p W}{F} \sum_i Q_i T_i DCF^S{}_{T,a,i}[\exp(-\lambda_i t_p)][1-\exp(-\lambda_i t_b)]$	(8)
	Swimming/Boating	$H^B{}_{T,a} = 4.03 \dfrac{U^B{}_a M_p}{F} \sum_i Q_i DCF^B{}_{T,a} \exp(-\lambda_i t_p) \times \dfrac{1}{GEOM}$	(9)

Table 2. **Notations for Equations**

Parameter	Unit	Description	Eqs used
D	[Gy/yr]	Absorbed Dose	(1),(2)
H_T	[Sv/yr]	Equivalent/Effective dose to tissue T	(2)~(9)
C	[Bq/m^3, Bq/m^2, Bq/kg]	Concentration in air, ground surface, or food	(4),(6)
Ᵽ/Q	[sec/m^3]	Atmospheric dispersion factor	(1)~(5)
F	[m^3/sec]	Flow rate of liquid effluents	(7)~(9)
W	-	Shore width factor	(8),(9)
M_p	-	Mixing ratio	(7)~(9)
GEOM	-	Geometry factor (1 for swimming, 2 for boating)	(9)
S_F	-	Shielding factor	(3),(4)
R_a	[m^3/yr]	Breathing rate	(5)
Q_i	[Bq/yr]	Annual release rate	(1),(2),(7)~(9)
DF	[Gy-m^3/Bq-sec]	Air absorbed dose coefficient	(1),(2)
DCF	[Sv-m^3/Bq-sec, Sv-m^3/Bq-sec,Sv/Bq]	Dose coefficient	(3)~(9)
Subscripts	n PATHWAYS (: gamma ray, $: beta ray, ∞ : air submersion, G : ground deposition, A : inhalation, I : ingestion, S: shoreline activity B: swimming/boating n FOOD V : produce, m : milk, F : meat, L : leafy vegetable n OTHERS i : nuclide, a : age group, T : tissue		

Radiation Dose Coefficients

Application of the dosimetric system of ICRP-60 means that dose coefficients derived from ICRP-60 series are applied to dose assessment. The ICRP[9,10,11,24] and USEPA[18] have provided a set of internal and external dose coefficients for use in environmental radiological dose assessment from routine releases. TEDII-60 uses these data as its own library in ASCII text file format. USEPA has evaluated external dose coefficients for more than 800 radionuclides using revised exposure geometry and current anthropomorphic phantom model. However, they do not consider different effect on exposed age groups, and they used tissue weighting factors provided in ICRP-26 to calculate the effective dose equivalent. Being the most recent data, these factors are used to calculate doses to the important tissues in ICRP-60 and it is assumed that younger age groups have the same doses as an adult. Table 3 shows how to combine equivalent doses of external and internal exposure to evaluate total doses to each important organ in ICRP-60. Although dose differences between adult and infant can vary as much as 40%[18], the effective dose equivalent calculated using former weighting factors does not deviate significantly from effective dose.[18,22] The task group of ICRP Committee 2 is now developing the external dose coefficients using new weighting factors, and will also consider different exposure effects on age groups. When it is available, this information will be incorporated in the TEDII-60 program.
The ICRP CD-ROM[24] of dose coefficients (published in 1999) is encoded into the TEDII-60 program. A CD-ROM gives inhalation dose coefficients for 10 aerosol sizes (0.001 to 10 μm AMAD) as well as ingestion dose coefficients. Effective doses and equivalent doses for all the important tissues (27 tissues for inhalation and 24 tissues for ingestion) for a range of integration times and for 6 ages are given. TEDII-60 accommodates these new dose coefficient features.

Table 3. Method for Summation of External and Internal Organs to Evaluate Total Dose

Organs in ICRP-60	Organs Calculated	
	External	Internal
Gonads	Gonads1)	Gonads3)
Bone Marrow(red)	Bone Marrow(red) 1)	Bone Marrow(red) 3)
Colon	*Remainder2)*	Colon3)
Lung	Lung1)	Lung3)
Stomach	*Remainder2)*	Stomach3)
Bladder	*Remainder2)*	Bladder3)
Breast	Breast1)	Breast3)
Liver	*Remainder2)*	Liver3)
Oesophagus	*Remainder2)*	Oesophagus3)
Thyroid	Thyroid1)	Thyroid3)
Skin	Skin1)	Skin3)
Bone Surface	Bone Surface1)	Bone Surface3)
Remainder	Remainder2)	Remainder3)

1) Organs evaluated using USEPA's external dose coefficients
2) Dose of remainder is considered as organ doses which are not included in USEPA's dose coefficient data.
3) Organs which are included in ICRP dose coefficient data.

Graphical User Interface

There are many input parameters for dose analysis, and it is difficult to prepare an input deck without making mistakes. Furthermore, it is time consuming work to analyze output results in detail. TEDII-60 resolves these problems by implementing graphical user interface programming.

All the processes for preparing input and analyzing output results are conducted with user-friendly interfaces via the PC. Figure 3 shows the main menu selection form of TEDII-60. User can enter the mode he wants via this form. Once a mode is selected, the user encounters an input form. Existing files can be opened or a new file can be generated in the input form. Input and output files are produced and stored as ASCII text file format, and the file name extensions are given automatically by the program according to their purpose.

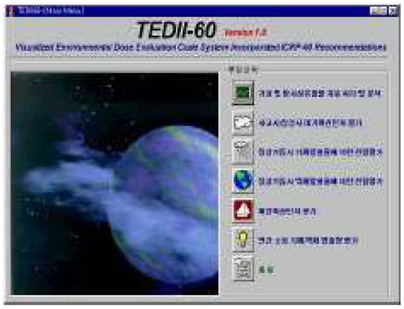

Figure 3. Mode selection form

Figure 4. Input Form

Simple input or output files are opened or saved directly by VB. Complicated files are read or written using Fortran DLL subroutines.

When creating a new input data, user is supported with default values and help form of TEDII-60. To prevent incorrect input parameters, an error-checking system is available to prompt the user with an error message at every important stage. An input form in the atmospheric dispersion routine is shown in Figure 4.

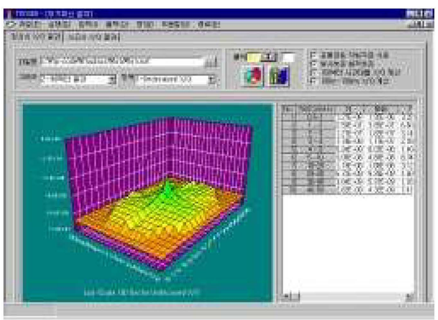

Figure 5. X/Q distribution graph

After the input file is saved, it is executed using a Fortran DLL subroutine which is initiated by the VB interface.

If the execution terminates successfully, output file(s) are generated. Since ASCII text file format output files are sometimes huge (up to several mega-bytes), Fortran DLL is used to read these files and transfers the resultant parameters to VB interfaces which display them graphically.

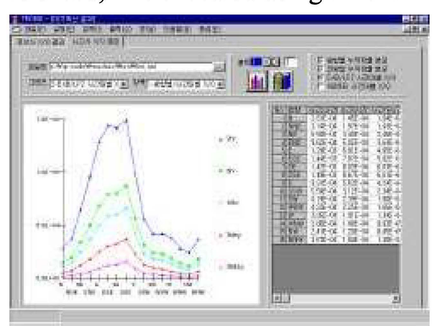

Figure 6. Directional X/Q graph

According to the type of output file, TEDII-60 generates various graphs which can be exported to any graphical file format for further manipulation. Figure 5 is a 3-D atmospheric dispersion distribution graph. The graph style can be changed with the graph control tool by clicking the right mouse button. Figure 6 is another type of graph representing directional dispersion factors.

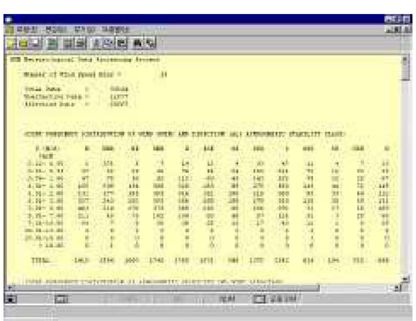

Figure 7. File editor of TEDII-60

The output result files can be viewed or edited by TEDII-60's own editor. The TEDII-60 editor provides the normal file editing abilities such as copying, searching, printing, etc. Figure 7 shows the editor of TEDII-60.

Code Validation and Sample Calculation

TEDII-60 code has been reviewed and tested by 3 independent bodies. KOPEC has performed a detailed review of its accuracy at every step of the calculation process by comparing to hand-calculated values. The Korean Institute of Nuclear Safety (KINS), the regulatory body of Korea, has tested TEDII-60 and compared the results with those from GASDOS which is another code developed at KINS to implement ICRP-60 recommendations. GASDOS is a modified code from USNRC's GASPAR.[4] The Nuclear engineering department of Han Yang University has also tested the code against their own methodology.
Two pre-existing codes were selected for comparison purposes. The first is the AZAP code developed by Sargent&Lundy Engineers LLC. Basic models, parameters and dose coefficients of this code are from USNRC Reg.Guide 1.109, and are fundamentally the same as GASPAR. Second is the GENII code[2] developed at Hanford Engineering Development Laboratory. It implements internal dosimetric models provided in ICRP-30 and uses Hanford's own pathway analysis models. Comparing results from these three codes shows historical trend of environmental radiological dose evaluation methods.

Table 4. Annual Expected Release rate for Ulchin Unit 3&4*

Gaseous Effluents (TBq/yr)				Liquid Effluents(TBq/yr)			
Nuclides	Rel. Rate	Nuclides	Rel. Rate	Nuclides	Rel. Rate	Nuclides	Rel. Rate
I-131	2.22E-3	Co-57	1.11E-6	Na-24	3.63E-4	Cd-109	-
I-132	1.18E-2	Co-58	5.11E-5	P-32	1.33E-5	Ag-110m	1.55E-4
I-133	7.33E-3	Co-60	1.04E-5	Cr-51	5.11E-4	Ag-110	8.88E-6
I-134	2.00E-2	Fe-59	3.77E-6	Mn-54	3.70E-4	Sn-113	-
I-135	1.41E-2	Br-82	-	Fe-55	5.99E-4	Sb-124	3.18E-5
H-3	8.14E+0	Sr-89	2.00E-5	Fe-59	1.78E-4	Sb-125	-
C-14	1.45E-1	Sr-90	8.14E-6	Co-57	-	Te-129m	9.62E-6
Ar-41	2.52E+0	Zr-95	7.40E-7	Co-58	8.14E-4	Te-129	1.33E-5
Kr-85m	4.14E+0	Nb-95	4.22E-6	Co-60	1.04E-3	Te-131m	2.29E-5
Kr-85	6.59E+1	Tc-99m	-	Ni-63	1.26E-4	Te-131	4.51E-6
Kr-87	1.48E+0	Ru-103	2.29E-6	Zn-65	2.74E-5	I-131	5.85E-3
Kr-88	5.11E+0	Ru-106	5.77E-8	W-187	3.03E-5	Te-132	5.03E-5
Xe-131m	5.85E+1	Ag-110m	-	Np-239	5.40E-5	I-132	6.14E-4
Xe-133m	5.92E+0	Sb-117	-	Br-84	4.37E-6	I-133	4.74E-3
Xe-133	2.29E+2	Sb-120	-	Rb-88	7.40E-6	I-134	2.15E-4
Xe-135m	5.18E-1	Sb-125	4.51E-8	Kr-88	-	Cs-134	1.85E-3
Xe-135	3.63E+1	Cs-134	5.11E-6	Sr-89	1.41E-5	I-135	2.59E-3
Xe-138	4.44E-1	Cs-136	4.44E-6	Sr-90	1.63E-6	Xe-135	-
Be-7	-	Cs-137	9.62E-6	Sr-91	4.74E-6	Cs-136	1.33E-4
Na-24	-	Ba-140	3.11E-7	Y-91m	2.89E-6	Cs-137	2.66E-3
Cr-51	1.33E-5	Ce-141	1.78E-6	Y-91	6.81E-6	Ba-137m	1.41E-3
Mn-54	7.40E-6	Ce-144	-	Y-93	2.07E-5	Ba-140	6.51E-4
		W-187	-	Zr-95	1.04E-4	La-140	8.88E-4
				Nb-95	1.55E-4	Ce-141	2.44E-5
				Zr-97	-	Ce-143	4.51E-5
				Mo-99	1.85E-4	Pr-143	8.88E-6
				Tc-99m	1.70E-4	Ce-144	5.03E-4
				Ru-103	4.07E-4	Pr-144	2.15E-4
				Rh-103m	3.92E-4	Po-210	-
				Ru-106	5.55E-3	H-3	7.47E+1
				Rh-106	4.88E-3		

*) Expected release rate from 2 unit operation

Due to the generic differences between these codes, it is impossible to use the exact same input data. Nevertheless, since most of the important parameters such as dispersion factors and usage

factors are the same, other differences between the codes can be considered negligible. A sample calculation was conducted for 1 unit operation of Ulchin Unit 3&4, which is the Korean standard pressurized light-water reactor. Doses from liquid effluents were not calculated because the doses are considerably lower than those of gaseous effluents. Table 4 shows expected gaseous and liquid effluent annual release rates calculated with the PWR-GALE code.
The summarized dose results are described in Table 5. Doses in Table 5 are for age group of “Adult”, because GENII can only evaluate adult doses while AZAP uses 4 age groups and TEDII-60 uses 6 age groups.

Table 5. Summarized Doses to Maximally Exposed Individual from Each Codes

Items		Calculated Results from		
		TEDII-60	AZAP	GENII
Doses to Adult from Gaseous Effluent (mSv/yr)	External Effective Dose*	3.54-3	6.63E-2	6.8E-3
	External Skin Equivalent Dose	1.01E-2	1.68E-2	-
	Internal Effective Dose	5.57E-3	5.04E-3	9.7E-3
	Internal Max. Organ Equivalent Dose**	1.76E-2	2.43E-2	3.4E-2

*) Dose from AZAP is “Whole body dose”, and that of GENII is “Effective dose equivalent”.
**) Maximally exposed organ of TEDII-60 and GENII is the thyroid, and that of AZAP is bone marrow.

The external dose calculated by TEDII-60 is lower than the dose from the other codes and internal dose is higher than the AZAP dose but lower than GENII dose. These differences are due to the differences in dose coefficients as is apparent in Figures 8 and 9.
Doses to several organs from various pathways are shown in Figure 8 and Figure 9.

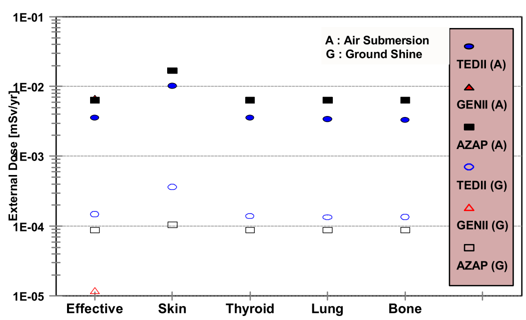

Figure 8. External Dose Comparison

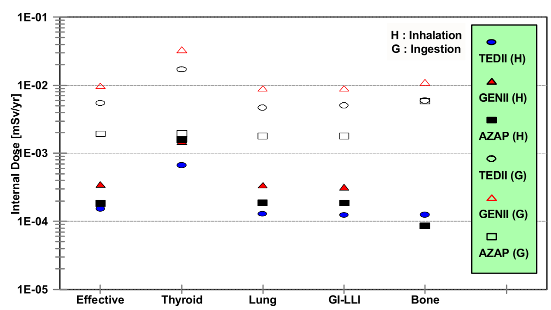

Figure 9. Internal Dose Comparison

Doses from the air submersion pathway are almost 100 times greater than ground shine doses in all codes. For the submersion pathway, doses from TEDII-60 is lowest due to the low dose coefficients of important nuclides Kr-88 and Xe-135 as shown in Figure 10. Air submersion doses calculated via GENII are the largest. Dose coefficient ratios of TEDII-60 to AZAP for those nuclides are 0.81 and 0.76, respectively. Doses from ground shine of TEDII-60 are highest among the three codes, followed by AZAP and GENII in descending order. Figure 10 supports this by showing the dose contribution of critical nuclides Co-60 and I-131. Since air submersion dose is much greater than the ground shine dose, the overall external dose from GENII is larger than doses determined via other codes, and TEDII-60 dose is the lowest.

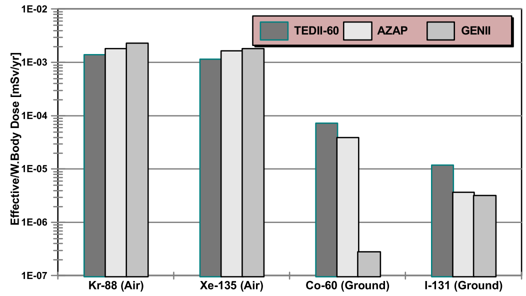

Figure 10. External Effective Doses from Critical Nuclides

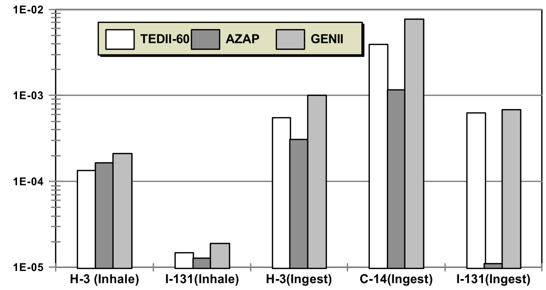

Figure 11. Internal Effective Doses from Critical Nuclides

Pathways for internal exposure are inhalation and ingestion of foods such as leafy vegetable, fruit, grain, other vegetables, milk and meat. Generally, doses from ingestion are 10 to 30 times higher than inhalation doses in all codes. For inhalation, TEDII-60 dose is lowest and GENII is the greatest. H-3 contributes more than 80% to the total inhalation dose. In the TEDII-60 calculation, tritiated water vapor was selected as the chemical form of tritium. The H-3 dose coefficient ratio of TEDII-60 to AZAP is about 0.42. For ingestion, C-14 is the most critical nuclide, and its chemical form in TEDII-60 calculation was selected as carbon dioxide. The C-14 dose in TEDII-60 is lower than GENII and higher than AZAP. The order of total internal doses from these three codes is the same as that of ingestion dose for C-14 doses, because doses from other important nuclides such as H-3 and I-131 have similar order to C-14 doses. The relative orders could be invalid if other source term distributions are used to dose calculation.

Summary

In order to meet the revised Korean regulation, the environmental pathway analysis software TEDII-60 was developed. The computer code incorporates recommendations of ICRP-60. Dose coefficient data for external pathways are based on the dosimetric system provided in ICRP-26, which are the most recent data from USEPA. Use of ICRP-26 dose coefficient data does not result in a significant deviation from dose results if ICRP-60 data were used. Internal dose coefficient data is used from latest ICRP publication which enables the evaluation of equivalent doses to a maximum of 27 organs for 6 public age groups. It also considers various types of chemical forms and aerosol sizes.

Procedures for preparing input and analyzing output results are conducted through user-friendly graphical interfaces which reduce errors and ensure smooth sessions. Output results are summarized in a report-formatted text file comparing calculated doses with regulatory guidelines. Self-produced graphs can be exported to various types of graphical files for further manipulation. The TEDII-60 code runs on personnel computers whose operating systems Windows 95, 98 or NT. Validation tests have been conducted by three independent bodies including the Korean regulatory institute showing excellent performance and full verification through comparison with pre-existing codes.

Currently Korean NPP utilities and designers devote much effort in both the design and operation with revised Korean nuclear regulations which have adopted ICRP-60 methodology. TEDII-60 will be used to evaluate compliance with ALARA design using for Safety Analysis and Environmental Reports as well as for annual offsite dose reports for currently operating plants.

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