Shielding Benchmark Calculation on a Multilayer One-dimensional Cylindrical Geometry with AETIUS, ANISN, and MCNPX

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1. Introduction

In a shielding analysis, several codes have been used. MCNP(X) [1] code has been widely used for providing reference or calculation results these days. However, ANISN [2], DORT [3], and TORT [4] are still in use even though they were developed in the 1960s, 1980s, and 1990s respectively.

ANISN is a Fortran IV program which solves one-dimensional Boltzmann transport equation for slab, cylindrical, or spherical geometry. DORT is two-dimensional and TORT is three-dimensional discrete ordinates transport codes which solve two- or three-dimensional geometry. Their principal application is to the deep-penetration transport of neutrons and photons.

Recently, mirror boundary condition capability on xy, yz, and zx planes is implemented in AETIUS such that we can handle one-dimensional cylindrical geometry even though AETIUS is a three-dimensional discrete ordinates code.

In this paper, we compared neutron, photon, and total flux distributions along radial direction on a multilayer one-dimensional cylindrical geometry with AETIUS, ANISN, and MCNPX.

2. Methods and Results

2.1 Brief overview of AETIUS

We have been developing discrete ordinates code, which is AETIUS (An Easy modeling Transport code usIng Unstructured tetrahedral mesh, Shared memory parallel) to benchmark Attila [5] code. AETIUS is programed using f90 and uses Gmsh [6] as a pre- and post- processing program. Before and after naming our code as AETIUS, it was tested on several applications [7,8,9,10] . MUST (Multi-group Unstructured geometry S_N Transport) is a twin code that programed with C++ [11,12]. The overall calculation flow of AETIUS is shown in Fig. 1.

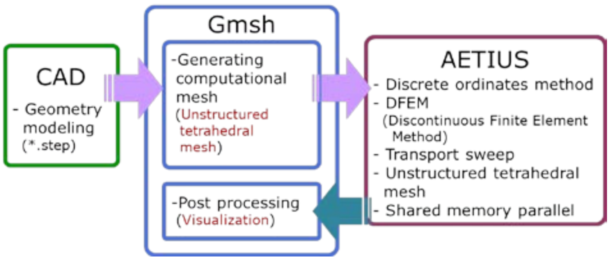

Fig. 1. The overall calculation flow of AETIUS.

2.2 Numerical Test

To check whether mirror boundary condition is implemented successfully or not, we chose a multilayer one-dimensional cylindrical geometry, which is shown in Fig. 2, as a shielding benchmark Test Problem.

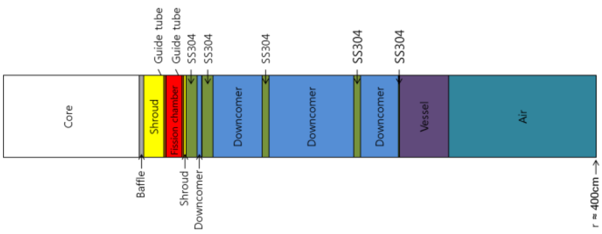

Fig. 2. A layout of shieling benchmark Test Problem (a multilayer one-dimensional cylindrical geometry).

For AETIUS calculation, shielding benchmark Test Problem is modeled as a quarter disk volume with 1cm thickness as shown in Fig. 3.

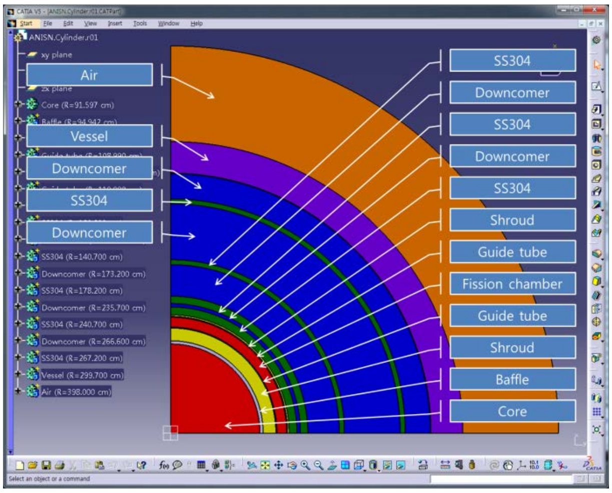

Fig. 3. Modeling of shielding benchmark Test Problem with CAD tool.

In order to change three-dimensional geometry into one-dimensional geometry, we apply mirror boundary conditions to the plane x=0 cm, y=0 cm, z=0 cm, and z=1 cm and vacuum boundary condition is applied to the arc surface like Fig. 4. By doing this, a quarter disk is changed to the multilayer one-dimensional cylindrical geometry and flux is only varying along radial direction.

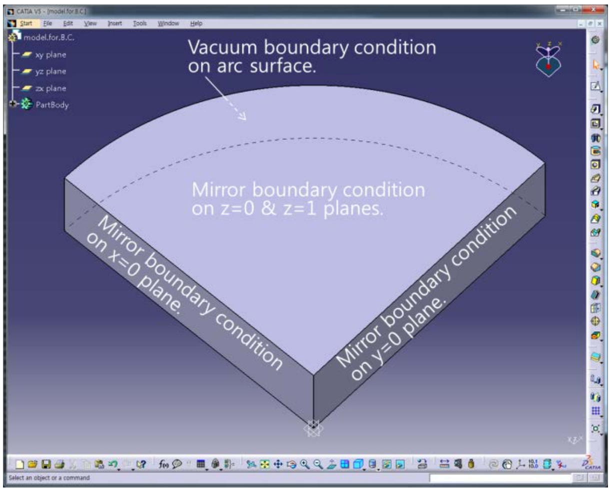

Fig. 4. Applied boundary conditions for shielding benchmark Test Problem.

The computational mesh is generated by Gmsh and shown in Fig. 5. To properly calculate the rapid flux change through relatively thin baffle, guide tube, fission chamber, and SS-304, we increase number of tetrahedral element up to 294,680.

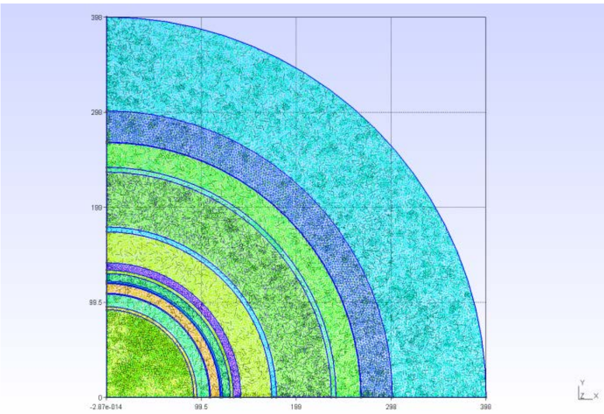

Fig. 5. The computational mesh (generated by Gmsh, 294,680 unstructured tetrahedrons).

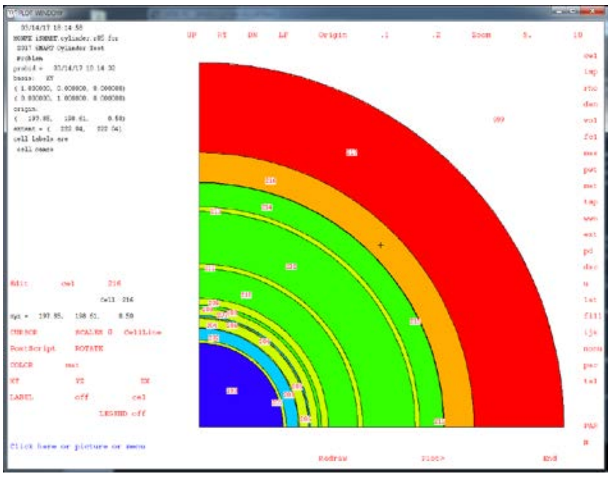

Fig. 6. The geometry modeling for MCNPX calculation.

We also prepared identical MCNPX input as Fig. 6. Same boundary conditions and cmesh (cylindrical mesh tally) tally are used to get a total neutron, total photon, and total fluxes along radial direction.

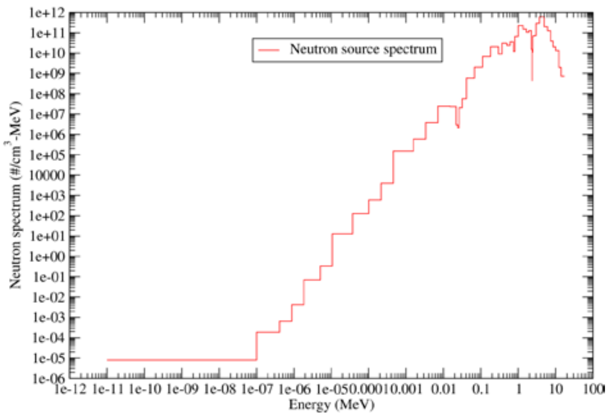

Fig. 7. Neutron source spectrum (47group structure, unnormalized).

The volume source is given in the core region with 47 group neutron spectrum shown in Fig. 7. All other calculation parameters for this calculation are listed in the Table I.

Table I: Calculation parameters

	MCNPX (Reference)	AETIUS	ANISN
Source strength	volume source: 5.71706×10^{12} neutron/cm^3-sec at core region		
Source spectrum	given in Fig. 6		
Library	ENDF-B/VII.0		BUGLE-96 ENDF-B/VI
Energy group structure	Continuous energy	Coupled 47 neutron, 20 gamma group structure	
Material (density & nuclides)	Core (density: 4.1800 g/cm^3) nuclides: 26 isotopes (cnat, h2, n14, n15, nb93, o17, si28, si29, si30, cr50, cr52, cr53, cr54, fe54, fe56, fe57, fe58, h1, o16, u235, u238, zr90, zr91, zr92, zr94, zr96)		
	Shroud (density: 6.0560 g/cm^3) nuclides: 27 isotopes (h2, o17, p31, s32, s33, s34, s36, si28, si29, si30, h1, o16, cnat, cr50, cr52, cr53, cr54, fe54, fe56, fe57, fe58, mn55, ni58, ni60, ni61, ni62, ni64)		
	Downcomer (density: 0.734904 g/cm^3) nuclides: 4 isotopes (h2, o17, h1, o16)		
	Baffle, Guide tube, Fission chamber, SS-304 (density: 7.769 g/cm^3) nuclides: 23 isotopes (p31, s32, s33, s34, s36, si28, si29, si30, cnat, cr50, cr52, cr53, cr54, fe54, fe56, fe57, fe58, mn55, ni58, ni60, ni61, ni62, ni64)		
	Vessel (density: 7.8420 g/cm^3) nuclides: 32 isotopes (mo92, mo94, mo95, mo96, mo97, mo98, mo100, p31, s32, s33, s34, s36, si28, si29, si30, v50, v51, cnat, cr50, cr52, cr53, cr54, fe54, fe56, fe57, fe58, mn55, ni58, ni60, ni61, ni62, ni64)		
	Air (density: 0.001293 g/cm^3) nuclides: 2 isotopes (n14, o16)		
Order of scattering anisotropy	n/a	3	5
S_N order	n/a	Rectangular Chebyshev-Legendre S_8	S_8

Number of tetrahedral element	n/a	294,680	167 (radial division)
Calc. options	mirror boundary condition on x=0, y=0, z=0, and z=1, vacuum boundary condition on arc surface.		n/a
Error criterion	nps:5×10^8	1×10^{-4}	
Parallel	MPI (121 cores)	OpenMP (120 cores)	n/a
Elapsed wall clock time	20.5 hour	50.05 hour	0.0068 min

The calculated total (neutron+photon) flux distribution of AETIUS is visualized through Gmsh. Based on the shape of iso-flux surface on the plane x=0 and y=0, we can conclude that mirror boundary condition is successfully implemented in the AETUS.

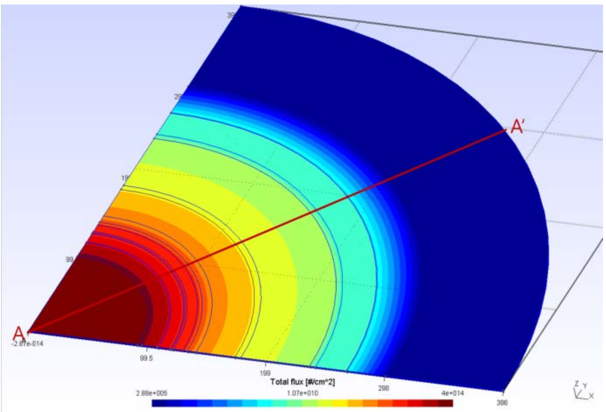

Fig. 8. Visualized total (neutron+photon) flux distribution of AETIUS.

Along AA' line in the Fig. 8, total neutron (1st - 47th group), total photon (48th - 67th group), and total (1st - 67th group) fluxes are compared and shown in Figures 9-11.

As we can see in Figs. 9-11, AETIUS provides very close result to the MCNPX reference result but slightly underestimate than that of MCNPX. However, the result of ANISN is more underestimate than any other two results.

The reason for this is that ANISN used BUGLE-96 library [13] (47 neutron and 20 gamma groups) which is collapsed from the VITAMIN-B6 fine-group (199 neutron and 42 gamma groups) library using LWR-specific material compositions and flux spectra. The BUGLE-96 cross sections are intended for use in LWR shielding and pressure vessel dosimetry applications.

However, AETIUS used identical group structure (47 neutron and 20 gamma groups) but it is not collapsed using any specific flux spectra and MCNPX used pointwise cross section library.

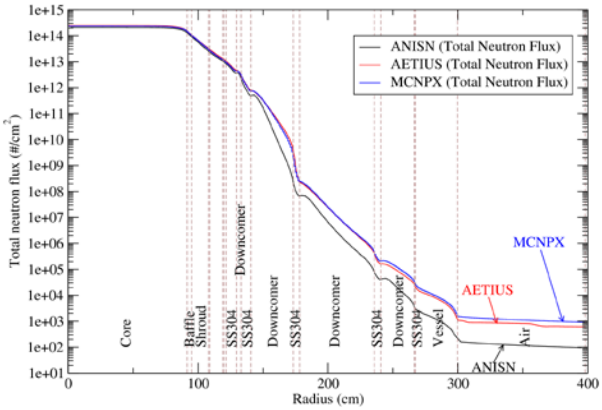

Fig. 9. Comparison of three total neutron fluxes along radial direction (AA' line).

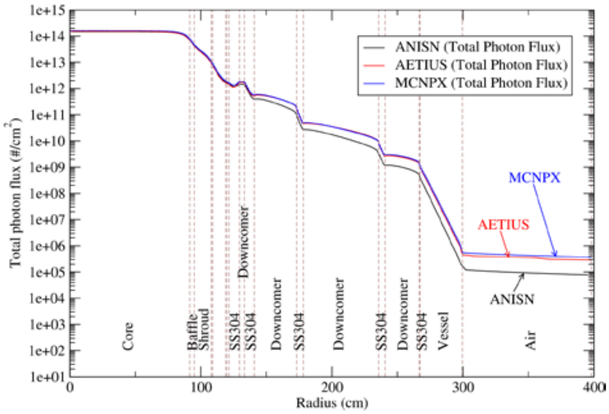

Fig. 10. Comparison of three total photon fluxes along radial direction (AA' line).

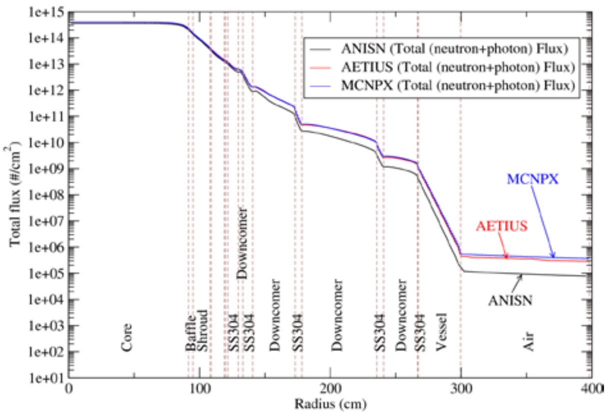

Fig. 11. Comparison of three total (neutron+photon) fluxes along radial direction (AA' line).

2.3 BUGLE-96 cross section library

In this section, we briefly introduce how BUGLE-96 cross section library was prepared. BUGLE-96 is coupled 47 neutron, 20 gamma-ray group cross section library derived from ENDF/B-VI for LWR shielding and pressure vessel dosimetry applications.

Overall procedure for collapsing fine-group cross sections using BWR- or PWR-specific flux spectra is shown in Fig. 12.

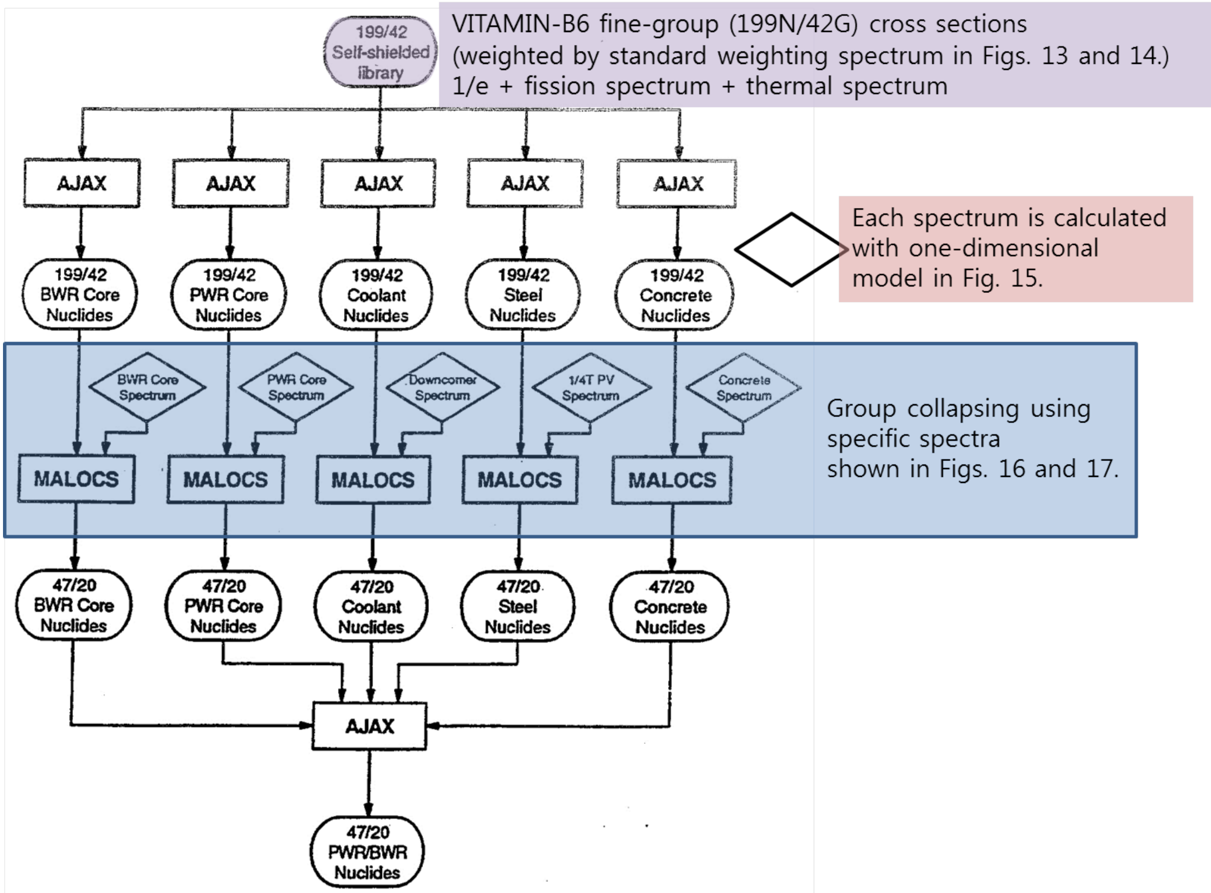

Fig. 12. Procedure for collapsing fine-group cross sections using BWR- or PWR-specific flux spectra (adapted from Ref. 13).

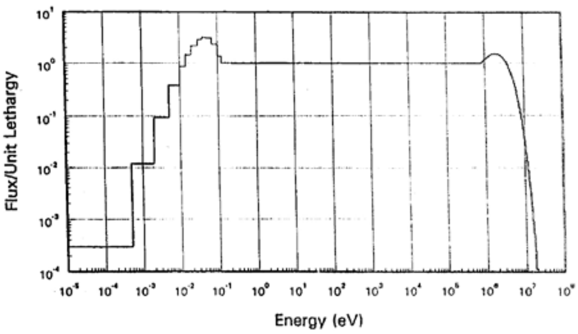

Fig. 13. 199-Group representation of standard weight spectrum used to create VITAMIN-B6 neutron cross sections from ENDF/B-VI pointwise data (adapted from Ref. 13).

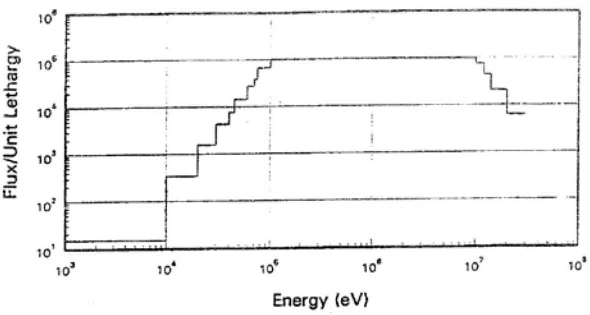

Fig. 14. 42-Group representation of standard weighting spectrum used to create VITAMIN-B6 gamma-ray cross sections from ENDF/B-VI pointwise data (adapted from Ref. 13).

First, VITAMIN-B6 fine-group (199 neutron and 42 gamma groups) are created using standard weighting spectrum shown in Figs. 13 and 14 in the NJOY [14] process. Then, make one-dimensional models to calculate the specific neutron and gamma flux spectra shown in Fig. 15. With these models, calculate the specific neutron and gamma flux spectra and results are shown in Figs. 16 and 17. These spectra are used for collapsing VITAMIN-B6 (199N/42G) fine-group cross sections to BUGLE-96 cross sections (47N/20G) library.

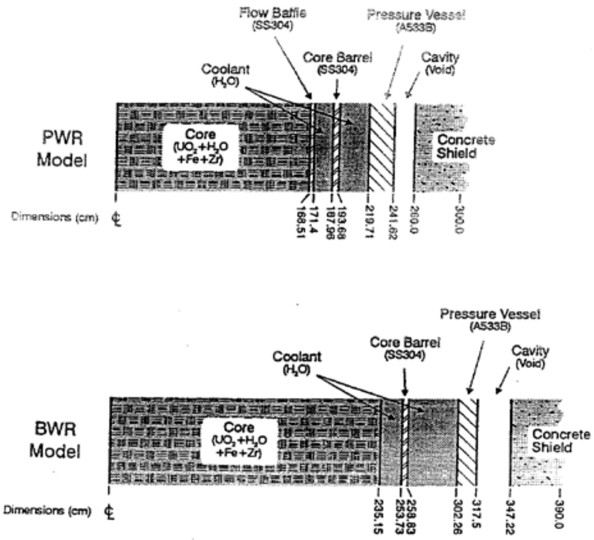

Fig. 15. One-dimensional models used to calculate the specific flux spectra for collapsing BUGLE-96 cross sections from VITAMIN-B6 (adapted from Ref. 13).

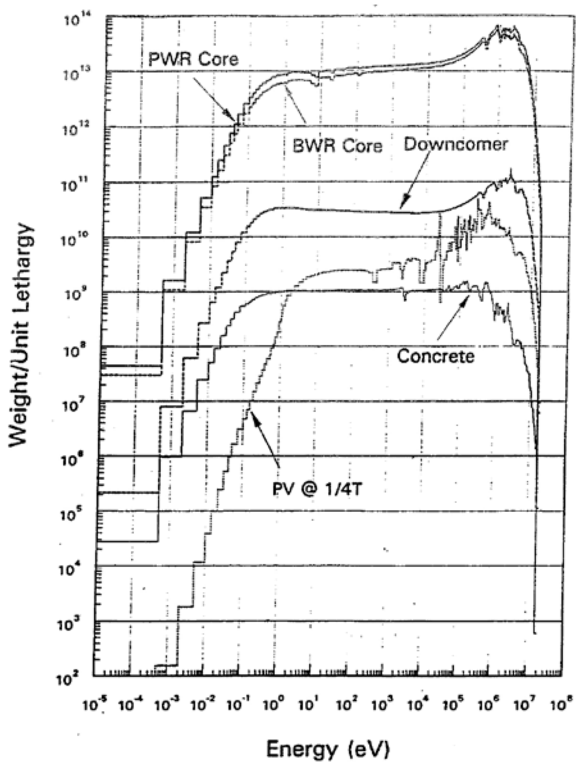

Fig. 16. Comparison of five BWR- or PWR-specific neutron flux spectra (adapted from Ref. 13).

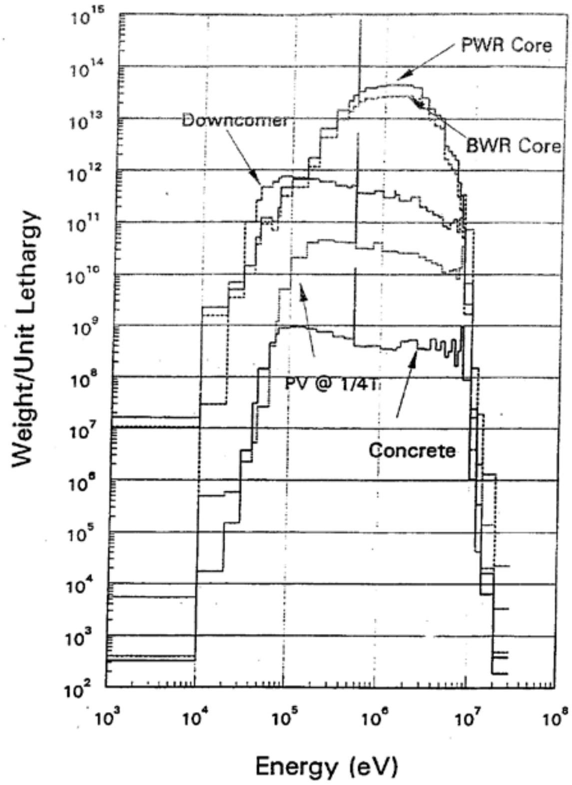

Fig. 17. Comparison of five BWR- or PWR-specific gamma-ray flux spectra (adapted from Ref. 13).

3. Conclusions

We compared neutron, photon, and total flux distributions along radial direction on a multilayer one-dimensional cylindrical geometry with AETIUS, ANISN, and MCNPX.

Three results should be same or similar but two calculation results of AETIUS and MCNPX are well match each other even though AETIUS results are slightly underestimate than that of MCNPX. However, the result of ANISN is different from other two results. In this Test Problem, ANISN should provide same results since ANISN is one-dimensional code for slab, cylindrical, or spherical geometry.

The reason for providing different results is that ANISN used BUGLE-96 cross section library, which is collapsed with PWR-specific neutron and gamma flux spectra, whereas AETIUS and MCNPX does not use it.

In order to explain why ANISN results are different from others, we also briefly introduced how BUGLE-96 cross sections library was prepared.

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