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CALCULATIONS OF ACTIVATION AND RADIATION SHIELDING OF SAMPLES IRRADIATED IN DALAT REACTOR USING ORIGEN2 AND QAD-CGGP2 CODES

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Calculations of Activation and Radiation Shielding of Samples Irradiated in Dalat Reactor Using ORIGEN2 and QAD-CGGP2 Codes

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The calculation of the necessary thickness of a lead container for the transportation of the TeO_2 and MoO_3 samples, which were irradiated in the Dalat reactor (fuel is U-Al alloy, 36% enrichment ^{235}U), is carried out by using ORIGEN2 and QAD-CGGP2 codes. In calculation, cross section library of PWR type (fuel is ^{235}U-low enriched UO_2) is used. For the convenience of comparison with experimental data, the calculation conditions are similar to the real conditions in the Dalat reactor. The calculation and experimental results were corresponding well each other in spite of the use of the cross section library of PWR type. It means that the calculations by using ORIGEN2 and QAD-CGGP2 codes with cross section library of PWR type are acceptable and could be used in calculations of activity and radiation shielding for different irradiation compositions in the Dalat reactor.

Keywords: Calculation, Activation, Radiation Shielding, Dalat Reactor, ORIGEN2, QAD-CGGP2, TeO_2 Target, MoO_3 Target, ^{131}I, ^{99m}Tc

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※ STA Scientist Exchange Program (Dalat Nuclear Research Institute, VIETNAM)

ＤＡＬＡＴ炉における照射サンプルの放射能および放射線遮蔽のＯＲＩＧＥＮ２及びＱＡＤ－ＣＧＧＰ２コードによる計算

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Tran Van HUNG※

（1998年６月17日受理）

ダラット研究所原子炉（ウラン－アルミニウム合金36％濃縮 ^{235}U燃料）において照射されたTeO_2およびMoO_3サンプルに関して輸送用鉛容器の必要厚さを、ORIGEN2コードおよびQAD-CGGP2コードで計算した。計算において、ORIGEN2内蔵のPWR型（低濃縮ウランUO_2の燃料）断面積ライブラリーを用いた。計算結果を実験データと比較しやすいように計算条件はできる限りダラット研究所原子炉での実験条件に合わせた。計算値と実験値は上記の断面積データの仮定にもかかわらず、よい一致を示した。このことから、ORIGEN2コードおよびQAD-CGGP2コード並びに，PWR型（低濃縮ウランUO_2の燃料）断面積ライブラリーを用いることに問題がないことが明らかとなり、今後のダラット研究所原子炉での他の照射サンプルについても放射能と必要な遮蔽の計算に利用できると考えられる。

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1. Introduction

The Dalat reactor is a pool type research reactor, which was re-constructed from a 250 kW TRIGA-MARK II reactor. During the reconstruction, the nominal reactor power was increased to 500 kW. The main purposes of the Dalat reactor are radioisotope production, neutron activation analysis, research and training. In the radioisotope production, samples are irradiated in the neutron trap with neutron flux about 2×10^{13}neutron $cm^{-2}s^{-1}$. Two main products in the Dalat reactor with high activity are ^{131}I and ^{99m}Tc, which are processed from irradiated TeO_2 and MoO_3 targets. After the irradiation, the samples are pulled out from the reactor core and placed in a lead container and transported from the reactor room to a hot cell by human power. Thus, the problem of radiation protection for workers should be considered by evaluating the necessary thickness of lead container.

In this report, the calculations of activation strength and the necessary thickness of lead container for the transportation of the irradiated samples, TeO_2 and MoO_3 , are described.

2. Calculation

2.1 Calculation Codes

Two calculation codes used in this problem are ORIGEN2 [1] and QAD-CGGP2 [2]. The ORIGEN2 code is used for calculating the photon characteristic of radio-nuclides produced in the irradiated samples during the reactor operation. It is a versatile point-depletion and radioactive decay computer code for use in simulating nuclear fuel cycles and calculating the nuclear compositions and characteristics of materials contained therein. It represents a revision and update of the original ORIGEN computer code, which was developed at Oak Ridge National Laboratory (ORNL) and distributed worldwide beginning in the early 1970s.

QAD-CGGP2 code is used for evaluation of dose at various points outside the lead container. It is a computer code for the shielding design of reactors, nuclear facilities and radioisotopes, developed in the Japan Atomic Energy Research Institute (JAERI). The QAD-CGGP2 is a point kernel calculation code and is the revised version of QAD-CGGP. In this version, the build-up factors for elements calculated with the DLC-15 photon cross section [3] are replaced by those calculated with the PHOTX photon cross section [4].

2.2 Calculation Conditions and Parameters

(1) Input Data for ORIGEN2 Code

To calculate radioactivity and photon characteristics of irradiation samples by using ORIGEN2, the necessary parameters for input are:

- Weight of ^{235}U in the reactor core
- Thermal power of reactor
- Weight of elements in target composition
- Irradiation time

For the present study, the above parameters are given in Table 1. Those parameters are the same as the real conditions in the Dalat reactor. In Appendix A, is shown the working configuration of the reactor core.

Table 1 The parameters for INPUT data of ORIGEN2 code

Parameter	Value
-Weight of ^{235}U (kg)	3,5
-Thermal power of reactor (kW)	500
-Weight of TeO_2 target (g)	100
-Weight of MoO_3 target (g)	5
-Weight of Al-container (g)	100
-Irradiation time (h)	100

The TeO_2 and MoO_3 targets are contained in an Al-container and irradiated in the central channel of reactor core. Thus, the target compositions are TeO_2+Al and MoO_3+Al. The Al-container is a cylinder with size of inner diameter 2 cm, thickness 3 mm and height 20 cm.

In the calculation, the cross sections library for PWR type was used and photon decay parameters are read from the photon decay library for activation products. A sample of input deck for ORIGEN2 code is shown in Appendix B.

(2) Input Data for QAD-CGGP2 Code

The output data of the ORIGEN2 calculation about the activity and the photon characteristics of radio-nuclides produced from the irradiated compositions of TeO_2+Al and MoO_3+Al were used as the input data for QAD-CGGP2 code. The geometrical parameters of the calculation configuration are shown in Fig 1. With this configuration, QAD-CGGP2 code makes use of the cylindrical coordinate system. The coordinate origin is at the center of the bottom of the lead container. Evaluation points are at half height of the lead container and at radial distance 0.0, 50 and 100 cm from the lead container surface. A sample of the input deck for QAD-CGGP2 code is shown in Appendix C.

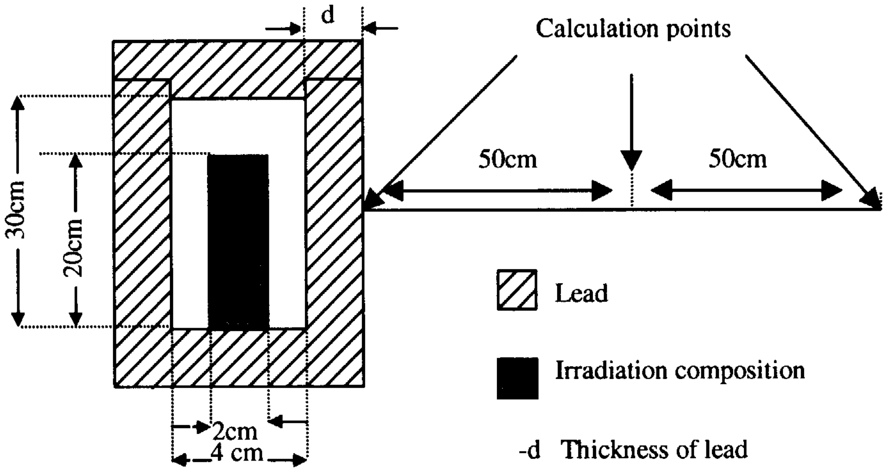


Fig.1 Lead container and irradiation composition for shielding calculation

3. Calculation Results and Discussions

A lot of information is given by ORIGEN2 output. However, only the information about activation products such as radioactivity, photon emission rate is necessary in the present problem. The radioactivity of nuclides was used for the comparison of the calculation results of ORIGEN2 with those calculated by using the basic activation equation. The basic activation equation is as follows:

$$A(Ci) = \frac{m\, \sigma_{act}\, \phi\, N_o}{A \times 3.7 \times 10^{10}} (1-e^{-\lambda T}) e^{-\lambda t}$$

where, m; weight of target isotope (g), σ_{act}; activation cross section of isotope (barn), ϕ; thermal neutron flux (n/cm^2/s) at irradiation position determined by experiment, N_o ; Avogadro number (6.023×10^{23}), A; mass number of target isotope, λ ; decay constant of radioisotope, T ; irradiation time, t ; cooling time.

The purpose of this comparison is to examine the adequacy of the use of the cross section for the PWR type in this case. In Table 2 are shown the activities of radio-nuclides produced in the activation process of TeO_2+Al and MoO_3+Al compositions. The comparisons revealed that the results by two methods are corresponding with each other. It indicates that the use of the cross section of PWR type in this problem is acceptable.

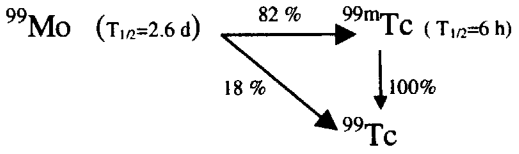
Table 2 **The calculated results of the activity of radio-nuclides produced in irradiation compositions TeO_2+Al and MoO_3+Al (irradiation time 100 h, cooling time 0 h)**

Radio-nuclides produced from TeO_2+Al		Activity (Ci)		Ratio (1)/(2)	Radio-nuclides produced from MoO_3+Al		Activity (Ci)		Ratio (1)/(2)
		(1)	(2)				(1)	(2)	
Al origin	^{24}Na	0.44	(*)		Al origin	^{24}Na	0.44	(*)	
	^{27}Mg	2.12	(*)			^{27}Mg	2.12	(*)	
	^{28}Al	50.8	(*)			^{28}Al	50.8	(*)	
Te origin	^{123m}Te	0.24	0.28	0.86	Mo origin	^{99}Mo	1.16	1.33	0.87
	^{127}Te	37.7	40.4	0.93		^{101}Mo	0.45	0.52	0.87
	^{129}Te	17.2	20.1	0.86		^{99m}Tc	0.97	1.14	0.85
	^{131}Te	5.90	6.53	0.92		^{101}Tc	0.45	0.48	0.94
	^{131m}Te	0.39	0.43	0.90					
	^{131}I	1.86	2.12	0.88					
Total		116.8			Total		56.4		

(1) Calculation by ORIGEN2 code.
(2) Calculation using basic activation equation with the experimental parameters
(*) Not calculated

In Table 2, the total activity of irradiation compositions includes two parts: the activity of target materials (TeO_2 and MoO_3) and activity of Al container. The energies of gamma rays emitted from the radio-nuclides created in TeO_2 and MoO_3 are mainly lower than about 1 MeV, while the energies of gamma rays emitted from radio-nuclides created in Al, are very high, especially, isotope ^{24}Na. The ^{24}Na is created from the reaction $^{27}Al(n,\alpha)^{24}Na$ ($E\gamma$=1368 keV, 2754 keV, $T_{1/2}$=15h). In this Table, all of the values of activity in the column (2) are higher than one in the column (1). It can be explained that the fuel used in the Dalat reactor is enriched to high concentration of ^{235}U (36%) compared with that of PWR. Therefore, the energy spectrum of the Dalat reactor is softer, specially, in the neutron trap because of the absence of uranium. The neutron flux used in ORIGEN2 is obtained by averaging in the all volume of active region, while, in the calculation using the basic activation equation with the experimental parameters, the neutron flux is the value in the neutron trap where it is the maximal value in the active region. These facts will give rise to column (1) values lower than those in column (2).

In the case of the calculation for MoO_3+Al composition, ^{99m}Tc is one of high activity isotopes. However, ^{99m}Tc does not appear in the original decay library of ORIGEN2. In the original decay library, only the transition $^{99}Mo \longrightarrow {}^{99}Tc$ is obtained. In ORIGEN2 code, the matrix exponential technique is used and the transitions with large decay constants are approximated to "instantaneous" ones; it means that, if the decay constant for B is large (i.e., B is short-lived) in a decay chain $A \rightarrow B \rightarrow C$, the matrix is reformulated as if C were formed from A directly. Thus, ^{99}Tc are directly formed from ^{99}Mo, and ^{99m}Tc does not appear in ORIGEN2 output. In the irradiation, ^{99}Tc is produced from ^{99}Mo by two branches. The decay scheme is as follows:



Therefore, in the present case, the decay data of ^{99m}Tc was filled up in the decay library.

The photon emission rates of the irradiated target composition in the output data of ORIGEN2 after 2 days cooling time are given in Table 3. The photon emission rate is given for each energy group as a function of cooling time. That is necessary as the input data of QAD-CGGP2 code. In ORIGEN2 code, the photon energy spectrum from 0 to 10 MeV is divided into 18 groups. However, in the present case, the photon energy spectrum is spread in the range from 0 to maximum 5 MeV and divided into 16 groups.

Table 3 The calculated results of the photon emission rate for irradiation compositions TeO_2+Al and MoO_3+Al by ORIGEN2 code (irradiation time 100 h, cooling time 2 days)

Upper energy of group (MeV)	Photon emission rate for TeO_2+Al (photons/s)	Photon emission rate for MoO_3+Al (photons/s)
1.000E-02	1.44E+10	8.11E+09
2.500E-02	1.28E+10	1.47E+09
3.750E-02	3.32E+09	1.18E+09
5.750E-02	2.19E+09	1.20E+09
8.500E-02	2.84E+09	6.91E+08
1.250E-01	2.17E+09	1.87E+09
2.250E-01	1.17E+10	1.77E+09
3.750E-01	4.90E+10	4.74E+08
5.750E-01	6.60E+09	7.62E+07
8.500E-01	5.43E+09	3.86E+09
1.250E+00	3.27E+09	1.93E+09
1.750E+00	1.39E+08	8.90E+03
2.250E+00	1.19E+08	7.62E+01
2.750E+00	1.77E+09	1.77E+09
3.500E+00	1.21E+06	1.21E+06
5.000E+00	1.26E+04	1.26E+04
Total	1.16E+11	2.44E+10

The calculated dose by irradiation composition TeO_2+Al at different distances is presented in Table 4 for different thickness of lead container. The calculated doses at 1 m from the lead container for TeO_2+Al and MoO_3+Al are compared in Table 5 and Fig. 2.

Table 4 The dose by TeO_2+Al calculated at different distances and for various thickness of lead container

Thickness of lead(cm)	Dose at various distances from lead container surface (mR/h)		
	0 cm	50 cm	100 cm
5.0	1539	46.4	14.0
6.0	600	26.7	7.90
7.0	281	15.6	4.70
8.0	132	9.1	2.85
9.0	62	5.4	1.71

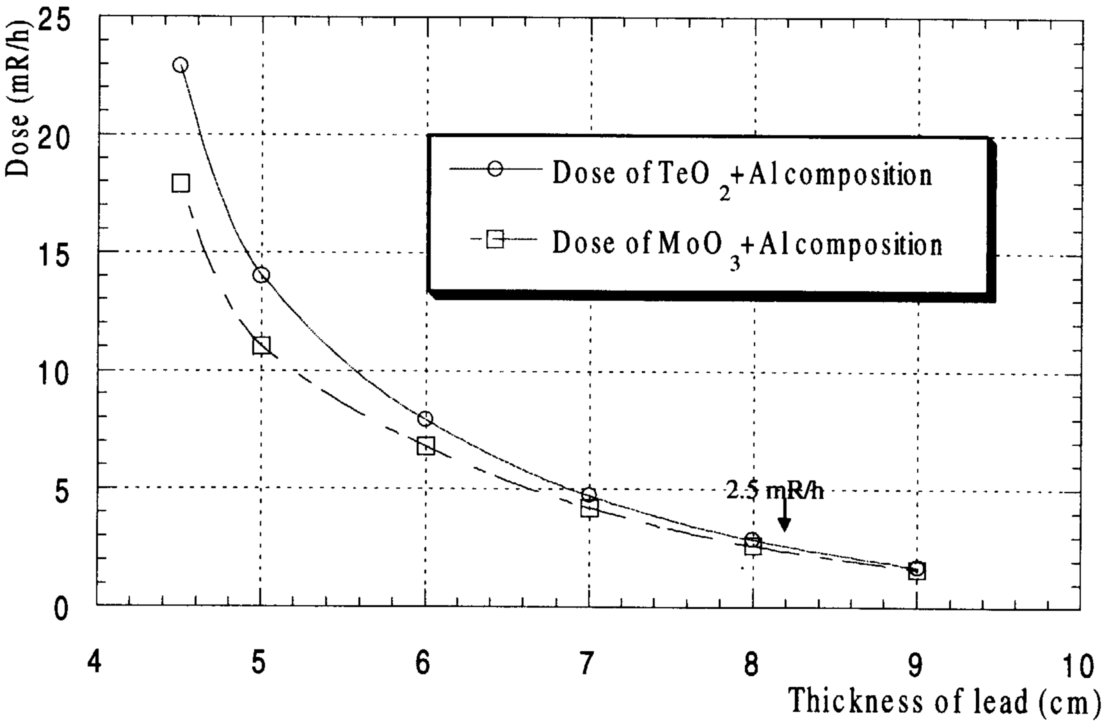


Fig. 2 The calculated dose for different thickness of lead container (Distance of 100 cm from the container surface)

Table 5 The calculated dose at distance of 100 cm from the lead container surface for TeO_2+Al and MoO_3+Al compositions

Thickness of lead container (cm)	TeO_2+Al composition (mR/h)	MoO_3+Al composition (mR/h)
4.5	22.8	17.8
5.0	14.0	11.0
6.0	7.90	6.75
7.0	4.70	4.18
8.0	2.85	2.60
9.0	1.71	1.61

Table 6 The calculated dose for various energy ranges of gamma rays at distance of 50 cm from lead container surface, thickness of lead container 5 cm.

Energy range (keV)	TeO_2+Al composition (mR/h)	MoO_3+Al composition (mR/h)	Al container (mR/h)
<300	<6.0 E-16	<1.0E-16	<1.0E-18
300 – 375	1.11E-03	1.12E-05	4.2E-07
375 - 575	2.61E-01	3.15E-03	2.6E-04
575 - 850	6.40E+00	3.23E+00	7.0E-04
850 - 1250	1.27E+1	7.80E+00	7.5E+00
1250 - 1750	1.18E-02	7.80E-05	2.8E-06
1750 - 2250	1.44E-03	9.40E-07	9.1E-07
2250 - 2750	2.63E+01	2.62E+01	2.62E+01
2750 - 3500	2.13E-02	2.12E-02	2.12E-02
3500 - 5000	2.72E-04	2.72E-04	2.72E-04
Total	46.32	38.10	34.00

Table 5 shows that the doses of TeO_2+Al and MoO_3+Al compositions are similar as the thickness of lead container increases. If the thickness of lead container is increased, the radiation dose outside of the lead container is mainly contributed by high-energy gamma-rays. This conclusion is also displayed in Table 6. Thus, the dose by ^{24}Na is an important part of the total dose in transporting the irradiation compositions in the lead container. The ^{24}Na, as above discussed, is created from reaction ^{27}Al(n,α)^{24}Na. The effective cross-section of this reaction depends on the neutron energy spectrum at the irradiation position. Therefore, the difference of energy spectra of the Dalat reactor and PWR should be considered. This problem will be studied in detail after this report.

Table 7 **The calculated and experimental doses at various distances from surface of lead container with thickness of 5 cm (Dose : mR/h)**

Distance from container(cm)	MoO_3+Al composition			TeO_2+Al composition		
	Calculation	Experiment	Cal/Exp.	Calculation	Experiment	Cal/Exp.
0	1451	1540	0.94	1539	1620	0.95
50	38.1	45	0.85	46.4	52	0.89
100	11.0	13	0.85	14.0	15	0.93

- Cal/Exp. is ratio of the calculated dose to experimental one

The calculated and measured doses are compared in Table 7 for the distances of 0, 50 and 100 cm from the surface of lead container. The experimental dose is measured with a dosimeter. The results showed that the difference between the calculated and experimental values is only about 5–15 %. It can be noticed in Table 2 that the activity of radio-nuclides calculated by ORIGEN2 is also about 5 – 15 % less than activity calculated by using a basic activation equation with experimental parameters.

From Fig.2 we can determine the necessary thickness of lead container. If we choose 2.5 mR/h as the acceptable dose level at distance 100 cm from the surface of lead container, the necessary thickness is 8.2 cm.

Thus, from the calculation and experimental studies, we conclude the following:

In spite of the use of the cross section library of PWR in the calculation, the calculation results for activity and dose of irradiation composition of TeO_2+Al and MoO_3+Al agreed with those by experimental methods within errors of about 5 - 15 %. Therefore, the calculations by ORIGEN2 and QAD-CGGP2 codes with the cross section library of the PWR type are acceptable for the activity and dose evaluation in the TeO_2 and MoO_3 irradiation. It will also be able to be applied to the estimations of activity and radiation shielding for different irradiation compositions in the Dalat reactor.

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References

[1] A. G. Croff., ORIGEN2 – A Revised and Updated Version of the Oak Ridge Isotope Generation and Depletion Code, ORNL-5621 (1980).

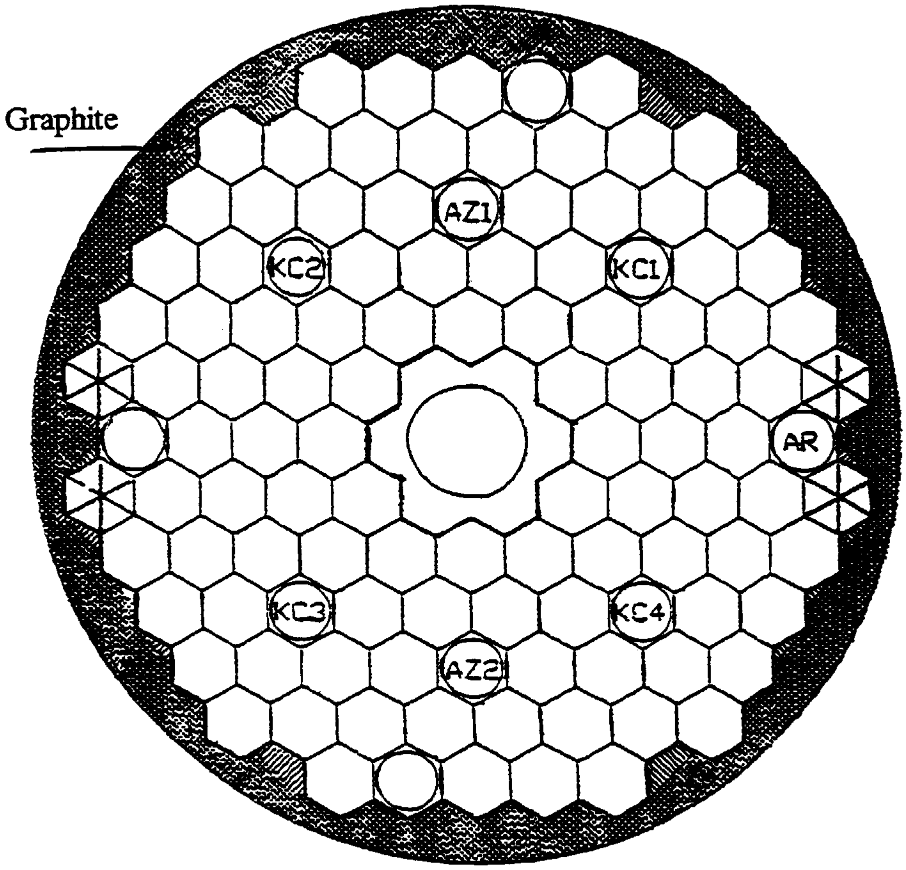
[2] Yukio SAKAMOTO and Shun-ichi TANAKA., QAD-CGGP2 and G33-GP2: Revised Versions of QAD-CGGP2 and G33-GP (Codes with the conversion factors from exposure to ambient and maximum dose equivalents), JAERI-M 90-110, July 1990.

[3] Oak Ridge National Laboratory Radiation Shielding Information Center Data Library Collection DLC-15, “Evaluated Photon Interaction Library ENDF/B Fil 23 Format” (1971)

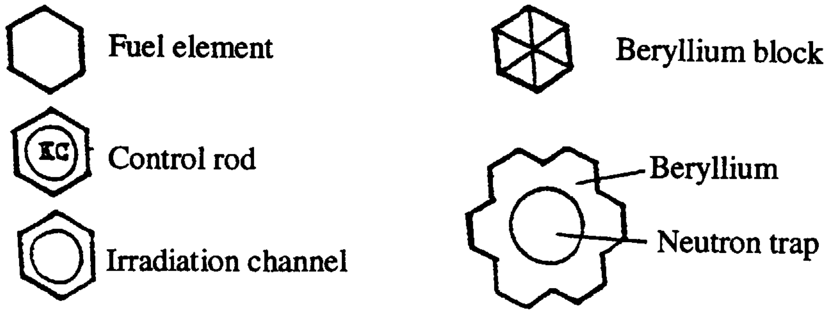
[4] Oak Ridge National Laboratory Radiation Shielding Information Center Data Package DLC-136,”PHOTX, Photon Interaction Cross section Library”.

Appendix A A plan view of the working configuration of the Dalat reactor core

The Dalat reactor core is cylindrical type, including 100 fuel rods of WWR-M2 bundle type, 7 control rods, 4 irradiation channels, graphite and beryllium blocks. The radius and height of active region are 20.8 cm and 60 cm, respectively. The working configuration of Dalat reactor is shown below.



Working configuration of Dalat reactor



Appendix B A sample of input deck for ORIGEN2 code calculating activity of TeO_2+Al composition

```

 92 1 1.0
-1
-1
-1
RDA      ORIGEN2, VERSION 2.1 (16-10-1997) SAMPLE PROBLEM
RDA      CALCULATION ACTIVITY OF TELLURIUM
BAS      100 GRAMS TELLURIUM
CUT      7 0.001 -1
LIP      0 0 0
LPU      -1
LIB      0 1 2 -3 -204 -205 -206 9 3 -2 0 0
PHO      -101 -102 -103 10
OPTL     4*8 7 8 7 17*8
OPTA     24*8
OPTF     24*8
TIT      COMPOSITIONS  OF  UNIT  AMOUTS  OF  TELLURIUM  AND
STRUCTION  MATERIALS
RDA      -1= READ FUEL COMPOSITION INCLUDING IMPURITIES (3.5 KG)
INP      -1 1 -1 -1 1 1
MOV      -1 1 0 1.0
HED      1
BUP
IRP      10.0 0.5 1 2  3 2
IRP      20.0 0.5 2 3 3 0
IRP      50.0 0.5 3 4 3 0
IRP      70.0 0.5 4 5 3 0
IRP      100.0 0.5 5 6 3 0
IRP      120.0 0.5 6 7 3 0
IRP      150.0 0.5 7 8 3 0
IRP      170.0 0.5 8 9 3 0
IRP      200.0 0.5 9 10 3 0
IRP      250.0 0.5 10 11 3 0
IRP      300.0 0.5 11 12 3 0
BUP
MOV      12 -10 0 1.0
STP      2
2        92340 0.0 92350 3500 922380 0.0 0 0.0
0
STP      2
RDA      -2=READ 100 GRAM TELLURIUM
```

```
INP    -2 1 -1 -1 1 1
RDA    -3=READ 100 GRAM ALUMINIUM
INP    -3 1 -1 -1 1 1
MOV    -2 1 0 1.0
ADD    -3 1 0 1.0
IRF    10.0 -1.0 1 2 3 4
IRF    20.0 -1.0 2 3 3 0
IRF    50.0 -1.0 3 4 3 0
IRF    70.0 -1.0 4 5 3 0
IRF    100.0 -1.0 5 6 3 0
IRF    120.0 -1.0 6 7 3 0
IRF    150.0 -1.0 7 8 3 0
IRF    170.0 -1.0 8 9 3 0
IRF    200.0 -1.0 9 10 3 0
IRF    250.0 -1.0 10 11 3 0
IRF    300.0 -1.0 11 12 3 0
OUT    12 1 -1 0
MOV    12 1 0 1.0
DEC    2.0 1 2 4 4
DEC    10.0 2 3 4 0
DEC    20.0 3 4 4 0
DEC    30.0 4 5 4 0
DEC    40.0 5 6 4 0
DEC    50.0 6 7 4 0
DEC    60.0 7 8 4 0
DEC    70.0 8 9 4 0
DEC    80.0 9 10 4 0
DEC    90.0 10 11 4 0
DEC    100.0 11 12 4 0
OUT    12 1 -1 0
OUT    -12 1 -1 0
END
4      520000 100.0 0 0.0
0
4      130000 100.0 0 0.0
0

```

Appendix C A sample of input data deck for QAD-CGGP2 code calculating dose outside of lead container
(distance from surface of lead container 50 cm, thickness of lead 5cm)

```
CALCULATION OF GAMMA RAY SHIELDING FOR IRRADIATED
TEO2+AL    COMPOSITION
10 40 52 1 1 1 16 1 0  1 1 0 0 0 0 0
1.0E+00 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.91.0
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0
9.5 10.0 10.5 11.0 11.5 12.0 12.5 13.0 13.5 14.0
14.5 15.0 15.5 16.0 16.5 17.0 17.5 18.0 18.5 19.0
19.5 20.0 20.5 21.0 21.5 22.0 22.5 23.0 23.5 24.0
0.0 0.025323 0.050645 0.075968 0.10129 0.12661 0.15194 0.17726
0.20258 0.22790 0.25323 0.27855 0.30387 0.32919 0.35452 0.37984
0.40516 0.43048 0.45581 0.48113 0.50645 0.53177 0.55710 0.58242
0.60774 0.63306 0.65839 0.68371 0.70903 0.73435 0.75968 0.78580
0.83411 0.88322 0.93234 0.98145 1.0306 1.0797 1.1288 1.1779
1.2270 1.2761 1.3252 1.3743 1.4235 1.4726 1.5217 1.5708
1.8850 2.1991 2.5133 2.8274 3.1416
GEOMETR DATA
RCC  1 0.000E+00 0.000E+00 5.010E+00 0.000E+00 0.00E+00 2.500E+01
        1.000E+00
RCC  2 0.000E+00 0.000E+00 5.000E+00 0.000E+00 0.000E+00 3.500E+01
        2.000E+00
RCC  3 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 4.000E+01
        7.000E+00
SPH  4 0.000E+00 0.000E+00 0.000E+01 1.000E+03
END
ZON  1
ZON  -1 2
ZON  -2 3
ZON  -3 4
END
     1  2  3  4
     1 1000 2 1000
     11  8  52  82
LEAD EXP 8.73 LEAD
0.3190 0.2720 0.0
0.0 0.0 11.34
0.0100 0.0250 0.0375 0.0575 0.0850 0.1250 0.2250 0.3750
```

```
0.5750 0.8500 1.25 1.75 2.25 2.75 3.5 5.0
1.44E+10 1.28E+10 3.32E+9 2.19E+9 2.84E+9 2.17E+9 1.18E+10 4.90E+10
6.60E+9 5.43E+9 3.27E+9 1.39E+8 1.19E+8 1.77E+9 1.21E+6 1.264E+4
3.05E-3 4.34E-4 1.981E-4 1.218E-4 1.327E-4 1.986E-4 4.042E-4 7.239E-4
1.119E-3 1.598E-3 2.182E-3 2.804E-3 3.339E-3 3.826E-3 4.496E-3 5.718E-6
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.01-5.00
0.01 0.025 0.0375 0.0575 0.0850 0.125
0.225 0.375 0.575 0.850 1.25 1.75
2.25 2.75 3.5 5.0
      PHOTONS      /CM**2/SEC   MR PER HOUR
57.1  19.0  0.0    0 0 0 0
   0     0   0    -1 0 0 0
```

国際単位系（SI）と換算表

表１　SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表３　固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m\cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー,仕事,熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表２　SIと併用される単位

名称	記号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ eV=1.60218\times10^{-19}J$

$1\ u=1.66054\times10^{-27}kg$

表４　SIと共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å=0.1nm=10^{-10}m

1 b=100fm^2=10^{-28}m^2

1 bar=0.1MPa=10^5Pa

1 Gal=1cm/s^2=10^{-2}m/s^2

1 Ci=3.7×10^{10}Bq

1 R=2.58×10^{-4}C/kg

1 rad=1cGy=10^{-2}Gy

1 rem=1cSv=10^{-2}Sv

表５　SI接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

(注)

1. 表1－5は「国際単位系」第5版，国際度量衡局1985年刊行による。ただし，1 eVおよび1 uの値はCODATAの1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換算表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘度　1 Pa·s(N·s/m^2)=10 P(ポアズ)(g/(cm·s))

動粘度　1m^2/s=10^4St(ストークス)(cm^2/s)

圧力	MPa(=10bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7 erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^{6}	3.67098×10^{5}	1	8.59999×10^{5}	3412.13	2.65522×10^{6}	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal= 4.18605J（計量法）

= 4.184J（熱化学）

= 4.1855J（15℃）

= 4.1868J（国際蒸気表）

仕事率　1 PS(仏馬力)

= 75 kgf·m/s

= 735.499W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

CALCULATIONS OF ACTIVATION AND RADIATION SHIELDING OF SAMPLES IRRADIATED IN DALAT REACTOR USING ORIGEN2 AND QAD-CGGP2 CODES