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Assessment of Occupational Exposure Due to Intakes of Uranium

원자력학회 춘계학술대회

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이 종 일

Korea Atomic Energy Research Institute

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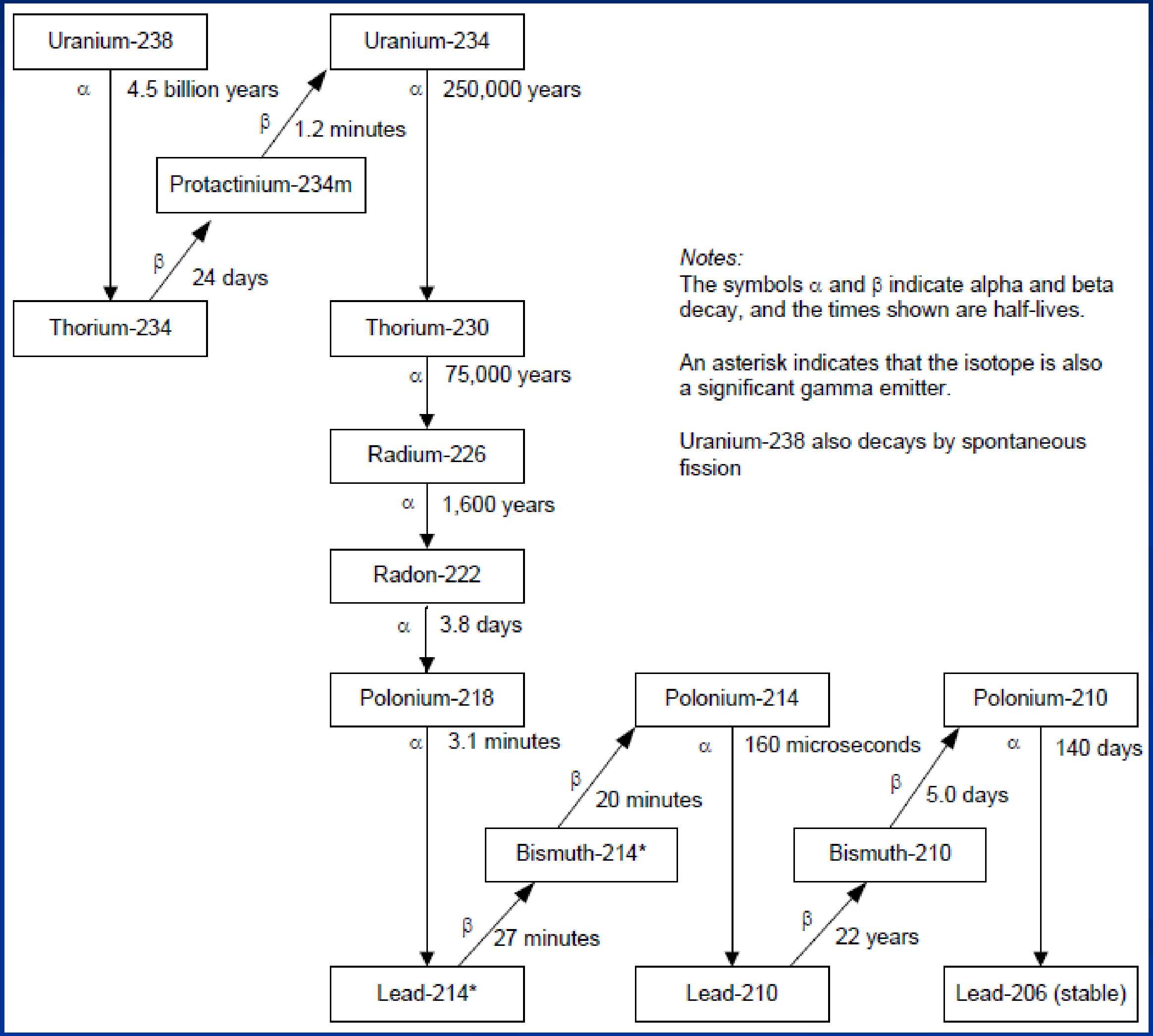
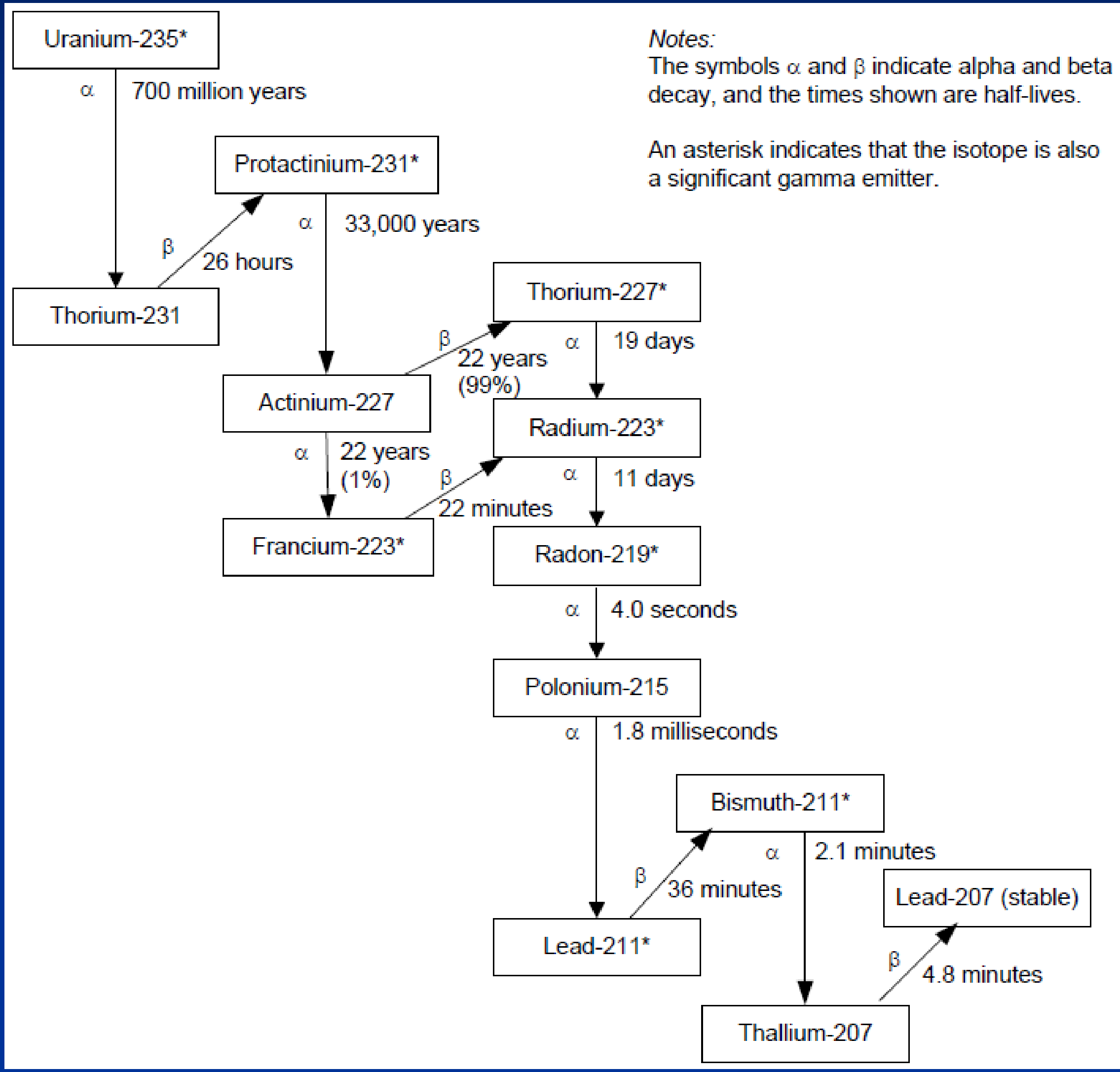
I. 우라늄 일반 정보

Decay Series for ^{238}U (^{234}U)



* Draft OIR(2012)

Decay Series for ^{235}U



* Draft OIR(2012)

Isotopic Composition of Natural Uranium

Isotope	% Isotopic composition	% Alpha activity	Alpha activity Bq/g
U-238	99.2745	48.16	1.23E+04
U-236	0.0000	0.00	0.00E+00
U-235	0.7200	2.25	5.76E+02
U-234	0.0055	49.59	1.27E+04
Total alpha activity, Bq/g			2.564E+04
Alpha activity ratio U-234/U-238			1.030
Alpha activity ratio U-235/U-238			0.047

[a] Composition is given as weight % of total U isotopes
[b] Alpha activity per gram uranium

* ICRP Supporting Guidance Document on Interpretation of Bioassay Data(2007)

Isotopic Composition of Enriched(3.5%) Uranium

Isotope	% Isotopic composition	% Alpha activity	Alpha activity Bq/g
U-238	96.471	14.73	1.20E+04
U-236	0.0000	0.00	0.00E+00
U-235	3.5000	3.44	2.7992E+03
U-234	0.02884	81.84	6.6679E+04
Total alpha activity, Bq/g			8.1478E+04
Alpha activity ratio U-234/U-238			5.556
Alpha activity ratio U-235/U-238			0.233

[a] Composition is given as weight % of total U isotopes
[b] Alpha activity per gram uranium

* ICRP Supporting Guidance Document on Interpretation of Bioassay Data(2007)

Isotopic Composition of Enriched(92.8%) Uranium

Isotope	% Isotopic composition	% Alpha activity	Alpha activity Bq/g
U-238	6.06	0.039	7.51E+02
U-236	0.34	0.428	8.16E+03
U-235	92.8	3.89	7.42E+04
U-234	0.79	95.64	1.82E+06
Total alpha activity, Bq/g			1.91E+06
Alpha activity ratio U-234/U-238			2452
Alpha activity ratio U-235/U-238			99.8

[a] Composition is given as weight % of total U isotopes
[b] Alpha activity per gram uranium

* ICRP Supporting Guidance Document on Interpretation of Bioassay Data(2007)

Isotopic Composition of Depleted Uranium

Isotope	% Isotopic composition	% Alpha activity	Alpha activity Bq/g
U-238	99.8000	83.39	1.24E+04
U-236	0.0000	0.00	0.00E+00
U-235	0.2000	1.07	1.60E+02
U-234	0.0010	15.53	2.31E+03
Total alpha activity, Bq/g			1.49E+04
Alpha activity ratio U-234/U-238			0.186
Alpha activity ratio U-235/U-238			0.013

[a] Composition is given as weight % of total U isotopes
[b] Alpha activity per gram uranium

* ICRP Supporting Guidance Document on Interpretation of Bioassay Data(2007)

Specific Activity

Nuclide	Half-life(b,c) (y)	Atomic mass(d) (u)	Specific activity (Bq/g)
U-234	$(2.457 \pm 0.003)\ 10^{5}$	234.0409456	2.3003E+08
U-235	$(7.037 \pm 0.007)\ 10^{8}$	235.0439231	7.9973E+04
U-238	$(4.468 \pm 0.005)\ 10^{9}$	238.0507826	1.2437E+04
U-236	$(2.342 \pm 0.003)\ 10^{7}$	236.0455619	2.3928E+06

(a) Avogadro's number 6.02214E+23
(b) Decay Data of the Transactinium Nuclides", IAEA Technical Report Series no. 261 (1986) (as recommended by NPL)
(c) 1 year = 365.2422 days as stated in Decay Data of the Transactinium Nuclides", IAEA Technical Report Series no. 261 (1986).
(d) NIST website (May, 2001)

* ICRP Supporting Guidance Document on Interpretation of Bioassay Data(2007)

^{235}U 질량% 에 따른 ^{234}U, ^{238}U 질량%

- ORNL (2012), E : % ^{235}U

$$\%^{234}U = 0.0015 + 0.0058E + 0.000054E^2$$

- 한전원자력연료㈜ (1987)

$$w/o\ \ U_{234} = \left(\frac{w/o\ \ U_{235}}{0.72}\right)^{1.08} \times 0.005$$

$$w/o\ \ U_{238} = 100 - w/o\ \ U_{235} - w/o\ \ U_{234}$$

II. 우라늄 내부피폭 감시

Direct measurement MDAs

Measurement category	Organ	MDA
I. Transuranium elements via x-rays	Lungs	185 Bq/A
II. ^{241}Am	Lungs	26 Bq
III. ^{234}Th	Lungs	110 Bq
IV. ^{235}U	Lungs	7.4 Bq
V. Fission and activation products	Lungs	740 Bq/A
VI. Fission and activation products	Whole body	740 Bq/A
VII. Radionuclides in the thyroid	Thyroid	740 Bq/A

* From ANSI 13.30
A is the number of photons per nuclear transformation – L x-rays for transuranium elements, and gamma rays for fission and activation products

Indirect measurement MDCs (urine)

Measurement Category	Nuclide	MDC
I Beta - Average energy ≤ 100 keV	^{3}H, ^{14}C, ^{35}S ^{147}Pm ^{210}P, ^{228}Ra, ^{241}Pu	370 Bq/L 0.37 Bq/L 0.19 Bq/L
II. Beta – Average energy > 100 KeV	^{32}P, $^{89/90}Sr$ or ^{90}Sr ^{131}I	0.74 Bq/L 3.7 Bq/L
III. Alpha – Isotopic specific measurements	^{210}Po, ^{226}Ra, $^{228/230/232}Th$, $^{234/235/238}U$ ^{237}Np, $^{238/239/240}Pu$, ^{241}Am, $^{242/244}Cm$	3.7 mBq/L 2.2 mBq/L
IV. Mass determination	Uranium (natural)	5 µg/L
V. Gamma or x-rays	Emitters with photons ≤ 100 keV	2 Bq L^{-1}/A
VI. Gamma or x-rays	Emitters with photons > 100 keV	2 Bq L^{-1}/A

* From ANSI 13.30
A is the number of photons per nuclear transformation – L x-rays for transuranium elements, and gamma rays for fission and activation products

Indirect measurement MDCs (faeces)

Measurement Category	Nuclide	MDA
VII. Alpha – Isotope specific measurements	$^{234/235/238}U$, $^{228/230/232}Th$, $^{238/239/240}Pu$, ^{241}Am	37 mBq/sample
VIII. Beta – Average energy > 100 keV	$^{89/90}Sr$ or ^{90}Sr	0.74 Bq/sample
IX. Gamma or x-rays	Emitters with photons ≤ 100 keV	2/A Bq/sample
X. Gamma or x-rays	Emitters with photons > 100 keV	2/A Bq/sample

* Minimum detectable concentration - From ANSI 13.30
A is the number of photons per nuclear transformation – L x-rays for transuranium elements, and gamma rays for fission and activation products

MTL Values for Direct Measurements

Measurement Category	Type	Radionuclide	MTL
I. Transuranium elements via L x-rays	Lung	^{238}Pu	9 kBq
II. Americium-241	Lung	^{241}Am	0.1 kBq
III. Thorium-234	Lung	^{234}Th in equilibrium w/ parent ^{238}U	0.5 kBq
IV. Uranium-235	Lung	^{235}U	30 Bq
V. Fission and activation products	Lung	Any two: ^{54}Mn, ^{58}Co, ^{60}Co, ^{144}Ce + ^{134}Cs & $^{137}Cs/^{137}Ba$	3 kBq 30 kBq 3 kBq
VI. Fission and activation products	Total body	All of: ^{134}Cs, $^{137}Cs/^{137m}Ba$, ^{60}Co & ^{54}Mn	3 kBq
VII. Radionuclides in the thyroid	Thyroid	^{131}I or ^{125}I	3 kBq

* ANSI HPS N13.30(1996)

MTL Values for Indirect Measurements

Measurement category	Radionuclide	MTL (per L or per sample)
I. BETA activity: average energy < 100keV	^{3}H, ^{14}C ^{35}S ^{228}Ra	2 kBq 20 kBq 0.9 kBq
II. BETA activity: average energy ≤ 100 keV	^{32}P $^{89, 90}Sr$ or ^{90}Sr	4 Bq
III. ALPHA activity: isotopic analysis	$^{228,/230}Th$ or ^{232}Th $^{234/235}U$ or ^{238}U ^{237}Np ^{238}Pu or $^{239/240}Pu$ ^{241}Am	0.02 Bq 0.02 Bq 0.01 Bq 0.01 Bq 0.01 Bq
IV. Elements (mass/volume)	Uranium	20 μg
V. GAMMA (photon) activity	$^{137}Cs/^{137m}Ba$ ^{60}Co ^{125}I	2 Bq 2 Bq 0.4 kBq

* ANSI HPS N13.30(1996)

Measurements Techniques for U

Isotope	Monitoring Technique	Method of Measurement	Typical Detection Limit	Achievable detection limit
^{234}U	Urine Bioassay	α spectrometry	0.3 mBq/L	0.05 mBq/L
^{234}U	Faeces Bioassay	α spectrometry	1 mBq/24h	0.2 mBq/24h

Isotope	Monitoring Technique	Method of Measurement	Typical Detection Limit	Achievable detection limit
^{235}U	Urine Bioassay	α spectrometry	0.3 mBq/L	0.05 mBq/L
^{235}U	Urine Bioassay	ICPM/S	0.001 μg/L (0.016 mBq/L)	8 E-07 Bq/L
^{235}U	Faeces Bioassay	α spectrometry	1 mBq/24h	0.2 mBq/24h
^{235}U	Lung Counting	γ-ray spectrometry	8 Bq	3 Bq
^{235}U	Whole Body Counting	γ-ray spectrometry	60 Bq	40 Bq

* Draft OIR(2012)

Measurements Techniques for U

Isotope	Monitoring Technique	Method of Measurement	Typical Detection Limit	Achievable detection limit
^{238}U	Urine Bioassay	α spectrometry	0.3 mBq/L	0.05 mBq/L
^{238}U	Urine Bioassay	ICPM/S	0.0015 μg/L (0.03 mBq/L)	0.002mBq/L
^{238}U	Urine Bioassay	TrKPA	0.1μg/L	0.06 μg/L
^{238}U	Urine Bioassay	Fluorimetry	1 μg/L	
^{238}U	Faeces Bioassay	α spectrometry	2 mBq/24h	0.2 mBq/24h
^{238}U	Lung Counting	γ-ray spectrometry of ^{234}Th	50 Bq of Th-234	30 Bq of Th-234

* Draft OIR(2012)

Typical uncertainties for U lung counting

Source of Uncertainty	Estimated Uncertainty
Chest Depth	12%
Chest Wall Thickness	15%
Activity Location	5%
Detector Placement	5%
Subject Background	10%
Calibration	5%
Counting Statistics	40%
Total Estimated Uncertainty	**90%**

* From Toohey, et al

Human Excreta

- **Drutman and Mordasheva (1985)**
  - Natural U, 24 h collection (254 women, 229 men)

    483 urine samples 1.4 ± 0.1 μg

    318 feces samples 2.3 ± 0.2 μg

- **ICRP-23 (1975)**
  - Reference Man

    Urinary excretion : 0.05 ~ 0.5 $\mu g \cdot d^{-1}$

    Fecal excretion : 1.4 ~ 1.8 $\mu g \cdot d^{-1}$

- **Wrenn et al. (1985)**
  - 37 samples : 0.098 ± 0.2 $\mu g \cdot L^{-1}$ ➡ 0.137 $\mu g \cdot d^{-1}$

    1.4 $L \cdot d^{-1}$

* NCRP SC 57-15 (1999)

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우라늄 일상감시 측정방법 및 최대 측정주기

물질	흡수형	체외분석		체내측정
		소변 (일)	대변 (일)	폐 (일)
육불화 우라늄	F	90	-	-
과산화 우라늄	F	30	-	-
질산염 우라늄	F	30	-	-
중우라늄산 암모늄	F	30	-	-
사불화 우라늄	M	90	180	180
삼산화 우라늄	M	90	180	180
8산화 우라늄	S	90	180	180
이산화 우라늄	S	90	180	180

비고 : 우라늄 혼합물의 방사성 및 화학 독성 모두 고려된다.

대변 시료 채집은 공기시료채집이 실제 섭취를 과소평가하지 않는다는 것을 확인하기 위해 권장된다.

* ISO 20553 (2006)

일상감시 측정주기 허용 오차

감시 간격 (일)	허용 오차 (일)
7	± 1
15	± 2
30	± 4
60	± 7
90	± 14
180	± 30
365	± 30

* ISO 20553 (2006)

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우라늄 흡입 후 특별감시 측정방법

방사성핵종	코		체외분석			체내측정		
			소변		대변	기관		
	NS	EA	spot sample	24 h	72 h	WB	L	Th
육불화 우라늄	**		**	**				
과산화 우라늄	**		**	**				
질산염 우라늄	**		**	**				
중우라늄산 암모늄	**		**	**				
사불화 우라늄	**		**	**	*		*	
삼산화 우라늄	**		**	**	*		*	
8산화 우라늄	**			**	**		**	
이산화 우라늄	**			**	**		**	

** = 권장됨, * = 보충적(의무가 아니라 보조적)

범례 : NS = 코 채취시료 EA = 호기 WB = 전신 L = 폐 Th = 갑상선

* ISO 20553 (2006)

내부선량에 따른 감시형태별 측정횟수

Radionuclide	Type of monitoring	Required monitoring data					
		D < 1 mSv		1 mSv ≤ D < 6 mSv		6 mSv ≤ D	
		Number	Time range (days)	Number	Time range (days)	Number	Time range (days)
U-235	Urine	-	-	2	30	3	60
	Faeces	1	-	2	30	3	60
	Lungs	-	-	2	60	4	120

* ICRP Guidance(2007)

III. 우라늄 내부피폭평가 도시메트리

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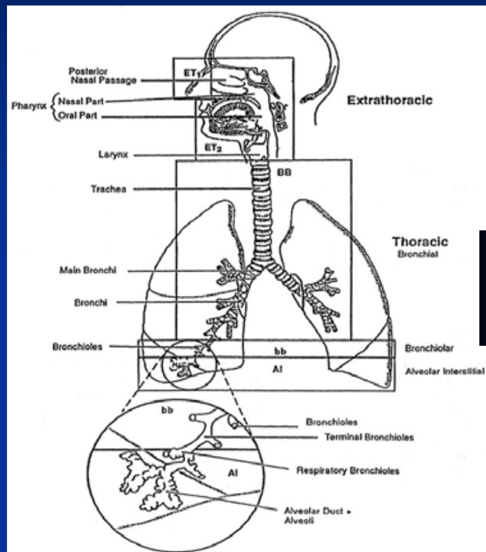
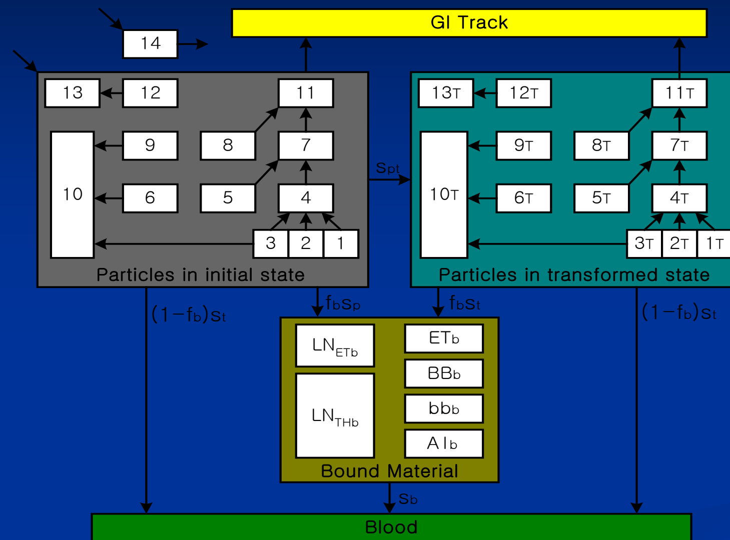
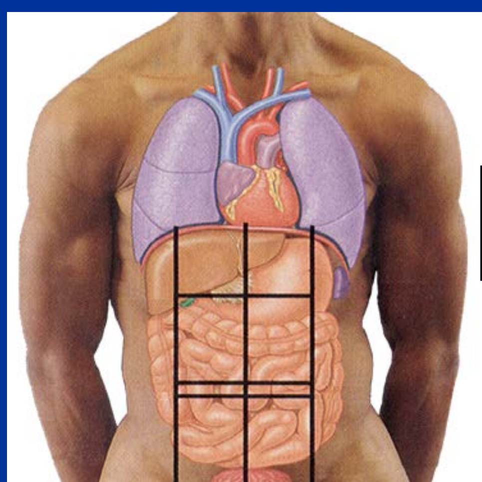
Compartment Model for Internal Dosimetry

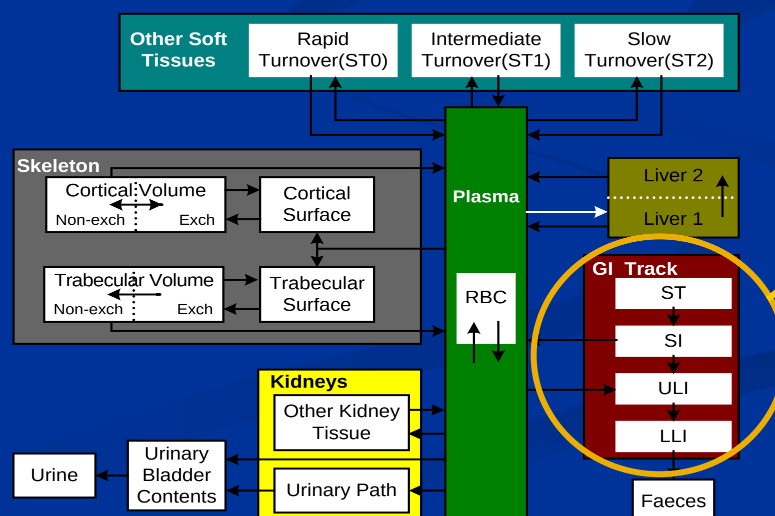
Respiratory tract model





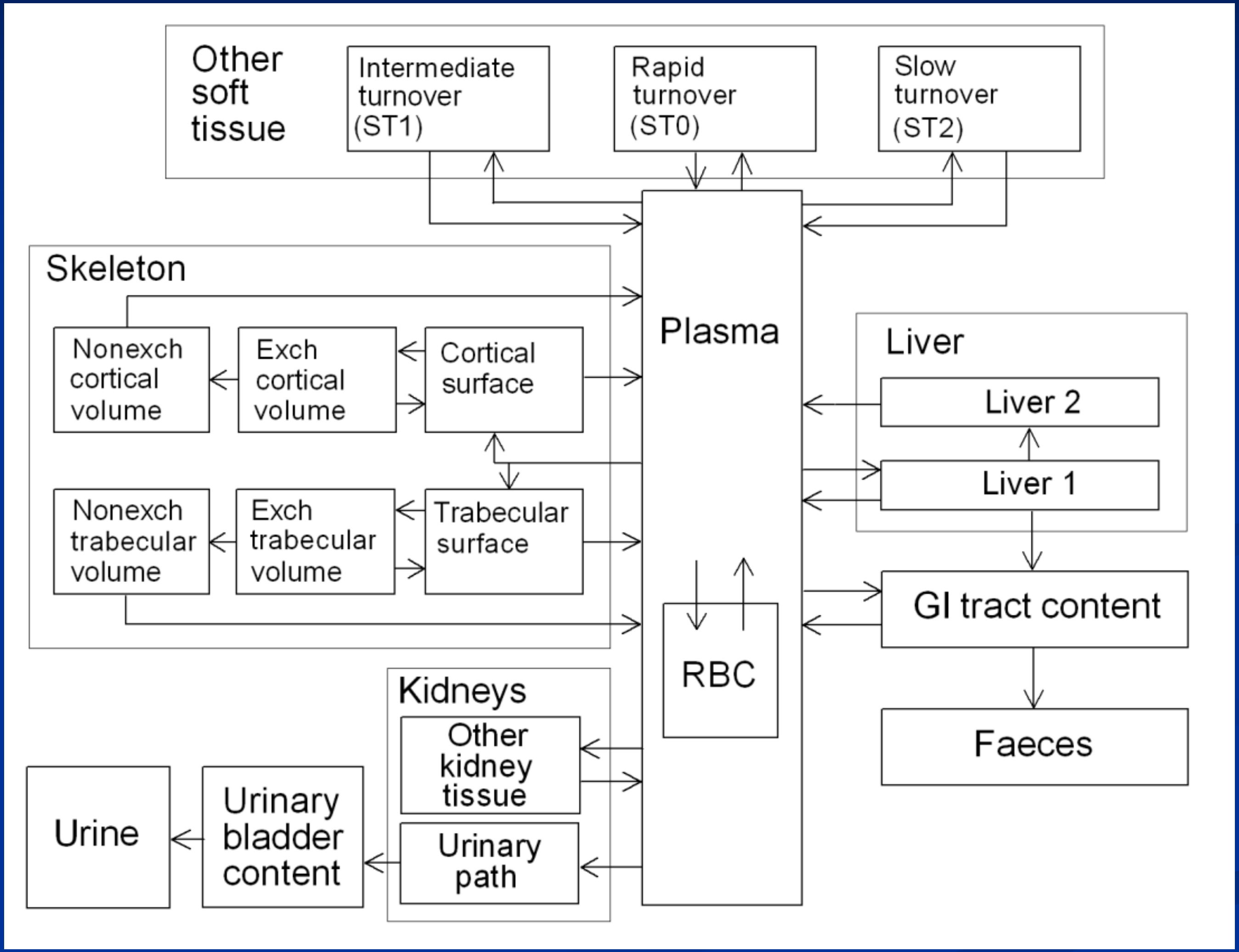
Biokinetic model





Gastrointestinal tract model

Diagram of the biokinetic model for U



* ICRP-69, 78 model, ICRP Guidance(2007), Draft OIR(2012)

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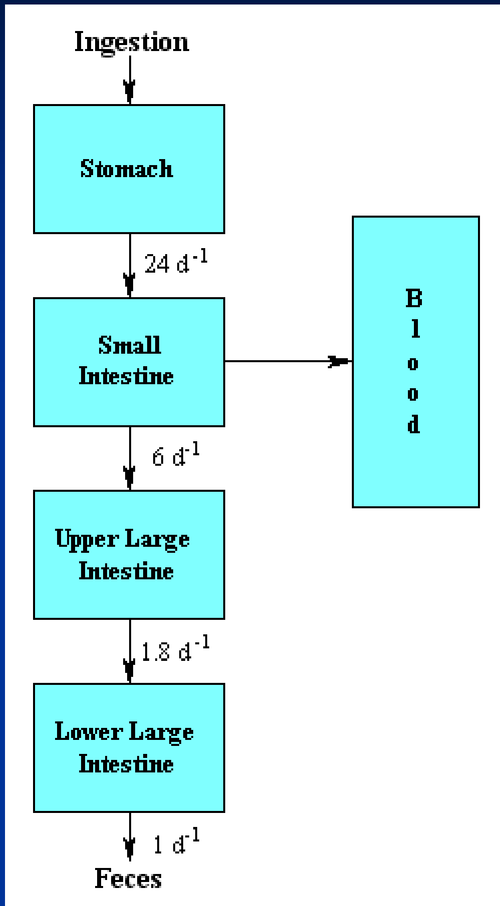
Transfer rates for the U systemic model (d^{-1})

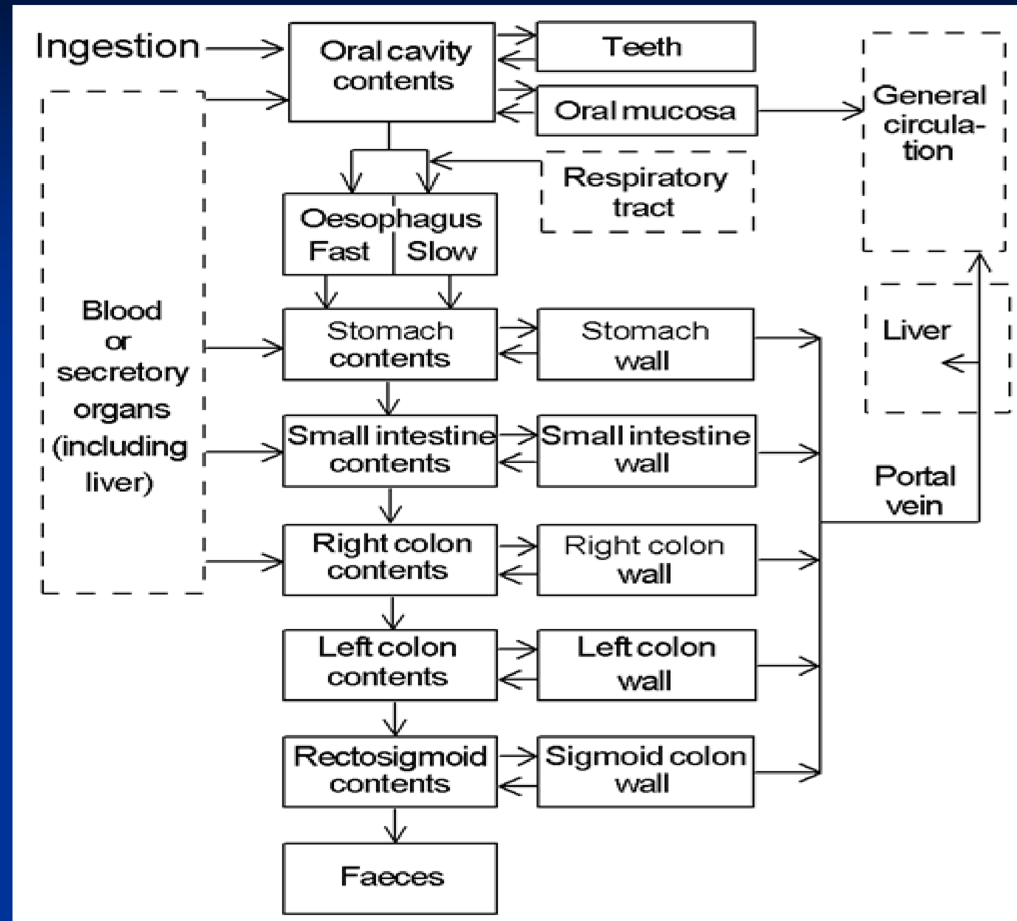
Plasma to ST0	1.05E+01
Plasma to RBC	2.45E–01
Plasma to urinary bladder	1.543E+01
Plasma to urinary path	2.94E+00
Plasma to other kidney tissue	1.22E–02
Plasma to ULI contents	1.22E–01
Plasma to liver 1	3.67E–01
Plasma to ST1	1.63E+00
Plasma to ST2	7.35E–02
Plasma to trabecular surfaces	2.04E+00
Plasma to cortical surfaces	1.63E+00
ST0 to plasma	8.32E+00
RBC to plasma	3.47E–01
Urinary path to urinary bladder	9.90E–02
Other kidney tissue to plasma	3.80E–04
Liver 1 to plasma	9.20E–02
Liver 1 to liver 2	6.93E–03
ST1 to plasma	3.47E–02
ST2 to plasma	1.90E–05
Bone surfaces to plasma	6.93E–02
Bone surfaces to exchangeable volume	6.93E–02
Liver 2 to plasma	1.90E–04
Non-exchangeable trabecular volume to plasma	4.93E–04
Non-exchangeable cortical volume to plasma	8.21E–05
Exchangeable bone volume to bone surfaces	1.73E–02
Exchangeable bone volume to non-exchangeable volume	5.78E–03

*ICRP-78(1997),
ICRP Guidance(2007),
Draft OIR(2012)

Human Alimentary Tract Model (HATM)



GI Tract Model (ICRP-30)



HATM (ICRP-100)

- Ingestion Retention Fraction : nearly same ($f_1 = f_A$)
- Committed Effective Dose : nearly same

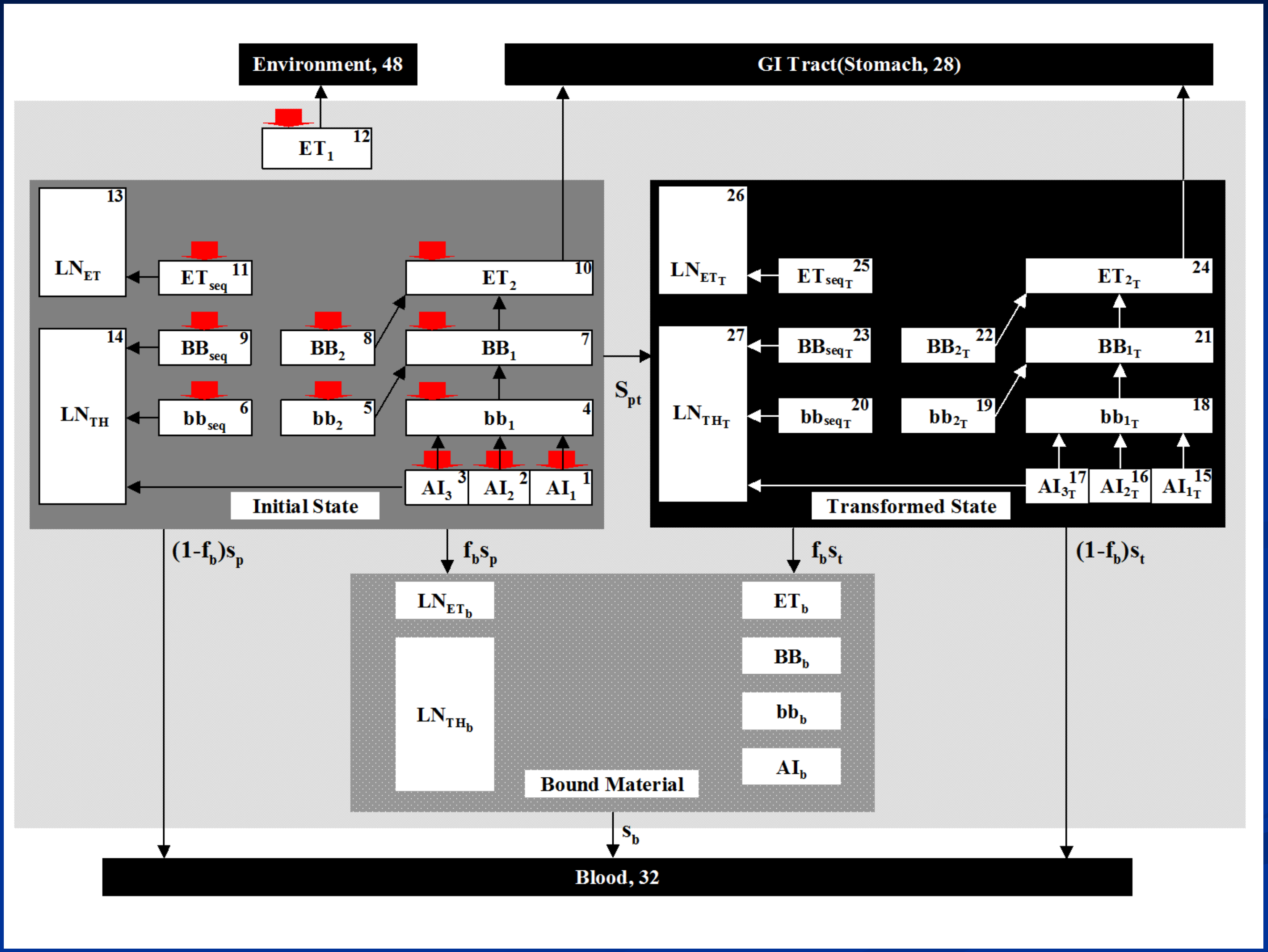
Human Alimentary Tract Model (HATM)

HAT model transfer coefficients for total diet for the reference worker

From	To	Transfer coefficient [c] (d^{-1})
Oral cavity contents	Oesophagus Fast	6480
Oral cavity contents	Oesophagus slow	720
Oesophagus Fast	Stomach contents	12343
Oesophagus Slow	Stomach contents	2160
Stomach contents	Small intestine contents	20.57
SI contents	Right colon contents	6
RC contents	Left colon contents	2
LC contents	Rectosigmoid contents	2
RS contents	Faeces	2

* ICRP-100(2006), ICRP Guidance(2007), Draft OIR(2012)

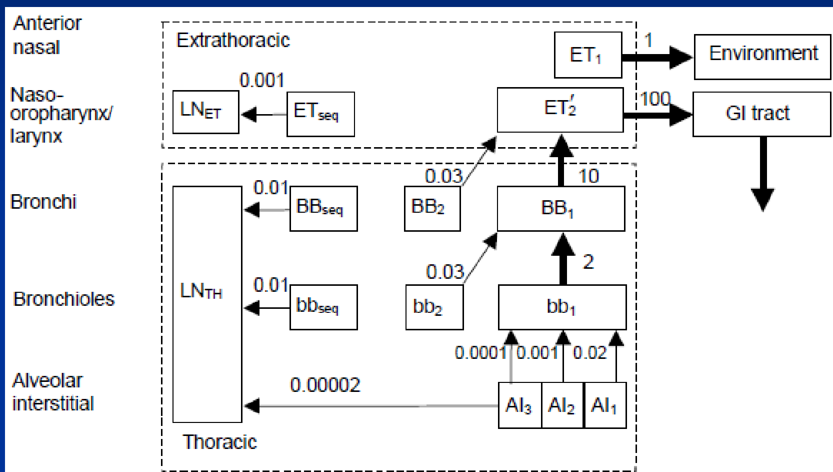
Human Respiratory Tract Model (HRTM)



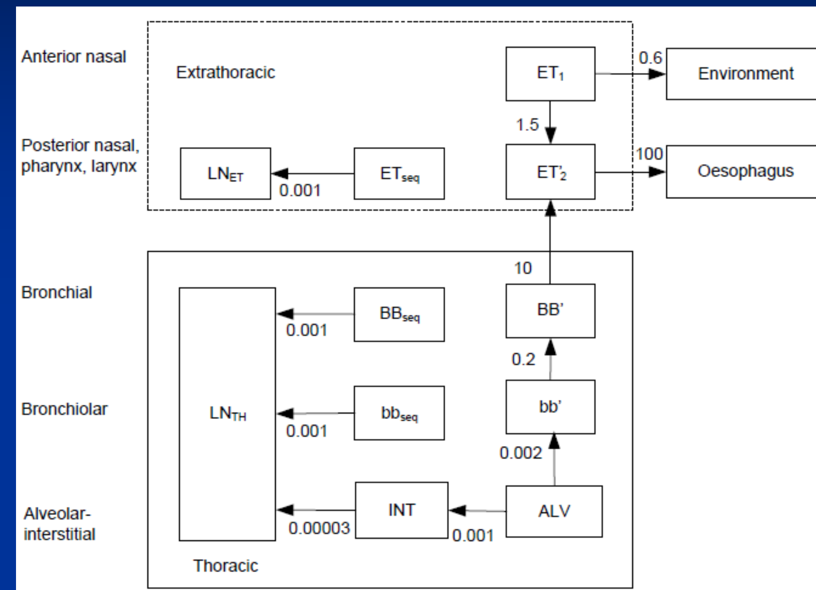
* ICRP-66, 78, ICRP Guidance(2007)

Human Respiratory Tract Model (HRTM)

ICRP-66(1993) Original HRTM (ICRP-78, ICRP Guidance(2007))



Draft OIR(2012) Revised HRTM



Region	Deposition (%) (5 μm) AMAD[a]
ET_1	34
ET_2	40
BB	1.8
Bb	1.1
AI	5.3
Total	82

Region	Deposition (%)[a,b,c]
	Male 5 μm AMAD
ET_1	47.94
ET_2	25.82
BB	1.78
bb	1.10
AI	5.32
Total	81.96

Regional deposition for Reference Workers engaged in light work

AMADs for different industries

Type of industry	Range of AMAD (μm)	Median (μm)	Recommended AMAD (μm)
All work places	0.12 - 25	4.4	5
Nuclear power industry	0.28 – 7.2	3.9	4
Uranium mills	0.5 - 16	6.8	7
Fuel handling facilities	0.34 – 16.5	3.8	4

ICRP Guidance(2007)

ICRP-78 Recommendation

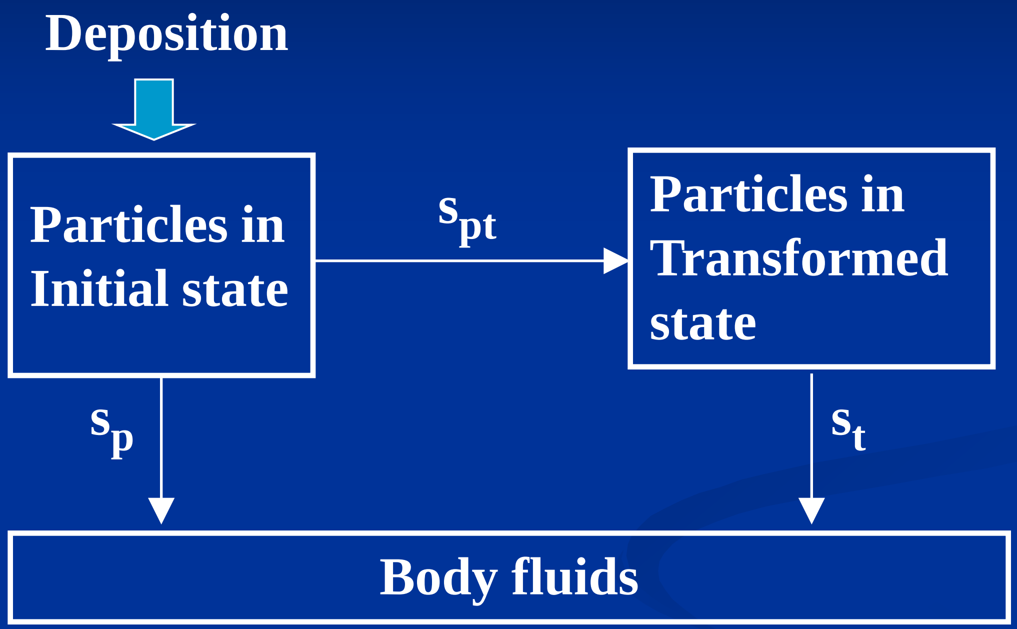
Absorption type

- Type F : 100% absorbed with a half-time of 10 minutes
- Type M : 10% absorbed with a half-time of 10 minutes and 90% with a half-time of 140 d
- Type S : 0.1% absorbed with a half-time of 10 minutes and 99.9% with a half-time of 7000 d

Absorption type for the compounds of uranium

Soluble compounds	: UF_6, UO_2F_2, $UO_2(NO_3)_2$	Type F
Less soluble compounds	: UO_3, UF_4, UCl_4	Type M
Highly insoluble compounds	: UO_2, U_3O_8	Type S

Compartment model representing time-dependent dissolution, followed by instantaneous uptake to body fluids (ICRP-66, 78)



Default absorption rates

Type	F (fast)	M (moderate)	S (slow)
Model parameters (d^{-1})			
s_p	100	10	0.1
s_{pt}	0	90	100
s_t	-	0.005	0.0001

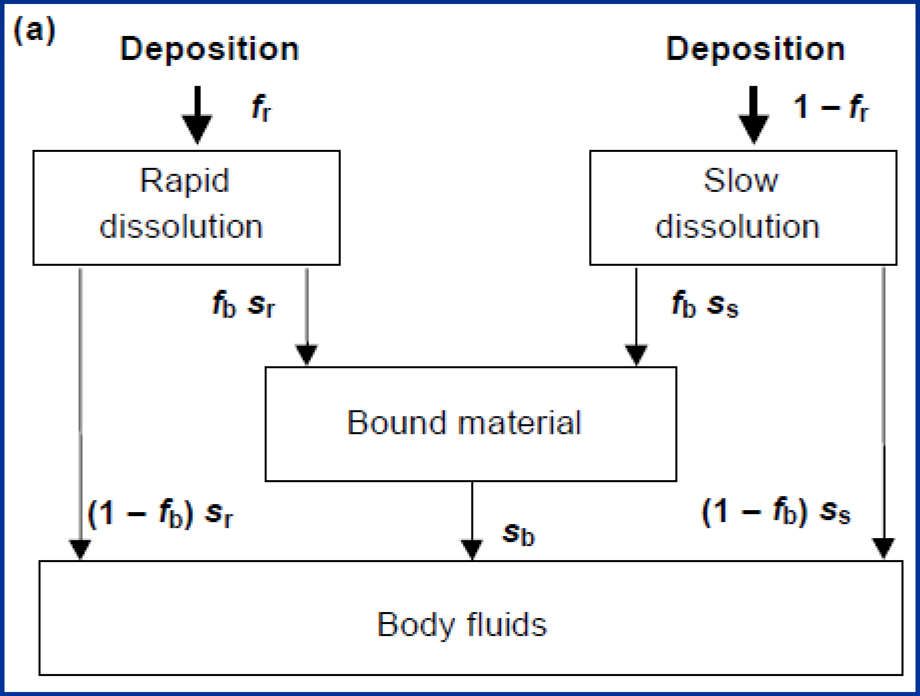
Draft OIR Part 3 (2012)

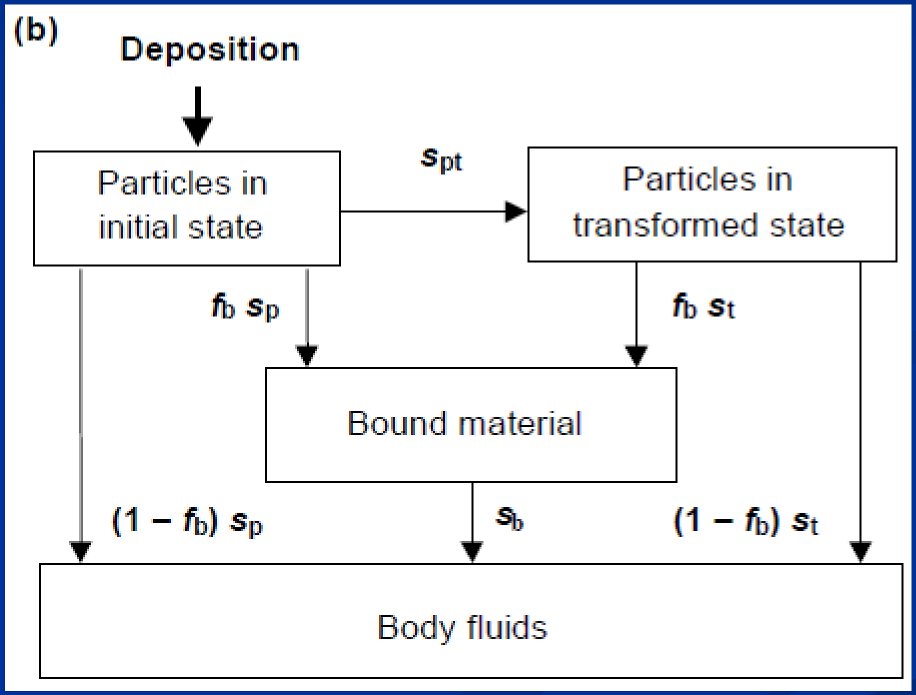
Update default absorption parameter values for Type F, M, S

Type V:	100% absorbed instantaneously. Regional deposition does not need to be assessed for such materials, because in dose calculations they can be treated as if they were injected directly into body fluids.
Type F:	100% absorbed with a half-time of ~30 minutes. There is rapid absorption of almost all material deposited in bb and AI, ~80% of material deposited in BB, and ~25% of material deposited in ET_2. The other material deposited in BB and ET_2 is cleared to the alimentary tract by particle transport.
Type M:	20% absorbed with a half-time of ~6 hours and 80% with a half-time of ~140 d. There is rapid absorption of ~20%, 5% and 0.5% of material deposited in bb, BB and ET_2, respectively. About 80% of the deposit in AI eventually reaches body fluids.
Type S:	1% absorbed with a half-time of ~6 hours and 99% with a half-time of ~7000 d. There is rapid absorption of ~1%, 0.25% and 0.03% of material deposited in bb, BB and ET_2, respectively. About 30% of the deposit in AI eventually reaches body fluids.

Draft OIR Part 3 (2012)

Alternative compartment models representing time-dependent absorption to body fluids





Draft OIR Part 3 (2012)

Absorption parameter for each compound of uranium

Inhaled particulate materials		Absorption parameter values[a] f_r	s_r (d^{-1})	s_s (d^{-1})	Absorption from the alimentary tract, f_A [d]
Specific parameter values[b]					
Uranyl Tri-Butyl-Phosphate (U-TBP)		0.97	12	0.002	0.02
Uranyl nitrate, $UO_2(NO_3)_2$		0.9	3	0.005	0.02
Uranium peroxide hydrate UO_4		0.9	0.9	0.02	0.01
Ammonium diuranate, ADU		0.8	0.7	0.02	0.02
Uranium trioxide UO_3		0.8	1	0.01	0.01
Uranium tetrafluoride UF_4		0.6	0.15	0.005	2×10^{-4}
Triuranium octoxide U_3O_8		0.04	1	6×10^{-4}	2×10^{-4}
Uranium dioxide UO_2		0.015	1	5×10^{-4}	2×10^{-4}
Uranium aluminide UAl_X		c	c	c	0.002
Default parameter values[d,e]					
Absorption Type	Assigned forms				
F	Uranium hexafluoride, UF_6	1	10	-	0.02
M	Uranyl acetylacetonate; DU aerosols from use of kinetic energy penetrators; vaporized U metal; all unspecified forms[f]	0.2	3	0.005	4×10^{-3}
S	—	0.01	3	1×10^{-4}	2×10^{-4}
Ingested materials					
Soluble forms (Type F)		–	–	–	0.02
Relatively insoluble forms (as assigned to Types M and S for inhalation)		–	–	–	0.002

Draft OIR Part 3 (2012)

Absorption parameter for each compound of uranium

a	It is assumed that for uranium the bound state can be neglected, *i.e.*, f_b = 0.0. The value of s_r for Type F forms of uranium (10 d^{-1}) is element-specific. The values for Types M and S (3 d–1) are the general default values.
b	See text for summary of information on which parameter values are based, and on ranges of parameter values observed for individual materials. For uranium specific parameter values are used for dissolution in the lungs, and where information is available for absorption from the alimentary tract. For other materials, the default value of f_A is used (footnote d).
c	See text: $s_p = 1 \times 10^{-4}\ d^{-1}$, $s_{pt} = 4 \times 10^{-3}\ d^{-1}$, $s_t = 4 \times 10^{-3}\ d^{-1}$, with f_A taken to be 0.002.
d	For inhaled material deposited in the respiratory tract and subsequent cleared by particle transport to the alimentary tract, the default f_A values for inhaled materials are applied: i.e., the (rounded) product of f_r for the absorption Type (or specific value where given) and the f_A value for ingested soluble forms of uranium (0.02).
e	Materials (e.g. UF_6) are listed here where there is sufficient information to assign to a default absorption Type, but not to give specific parameter values (see text).
f	Default Type M is recommended for use in the absence of specific information, *i.e.*, if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

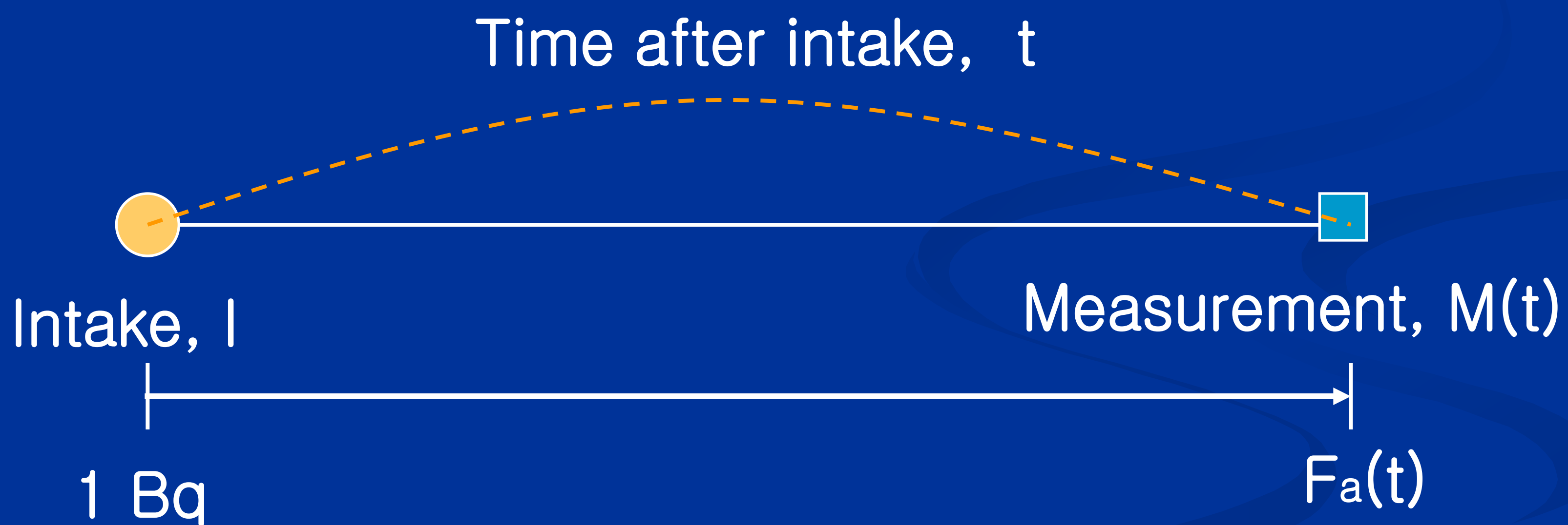
Internal Dose Assessment [Sv/Bq]

Acute Intake I_A

$$I_A = \frac{M(t)}{F_a(t)}$$

Chronic Intake I_c

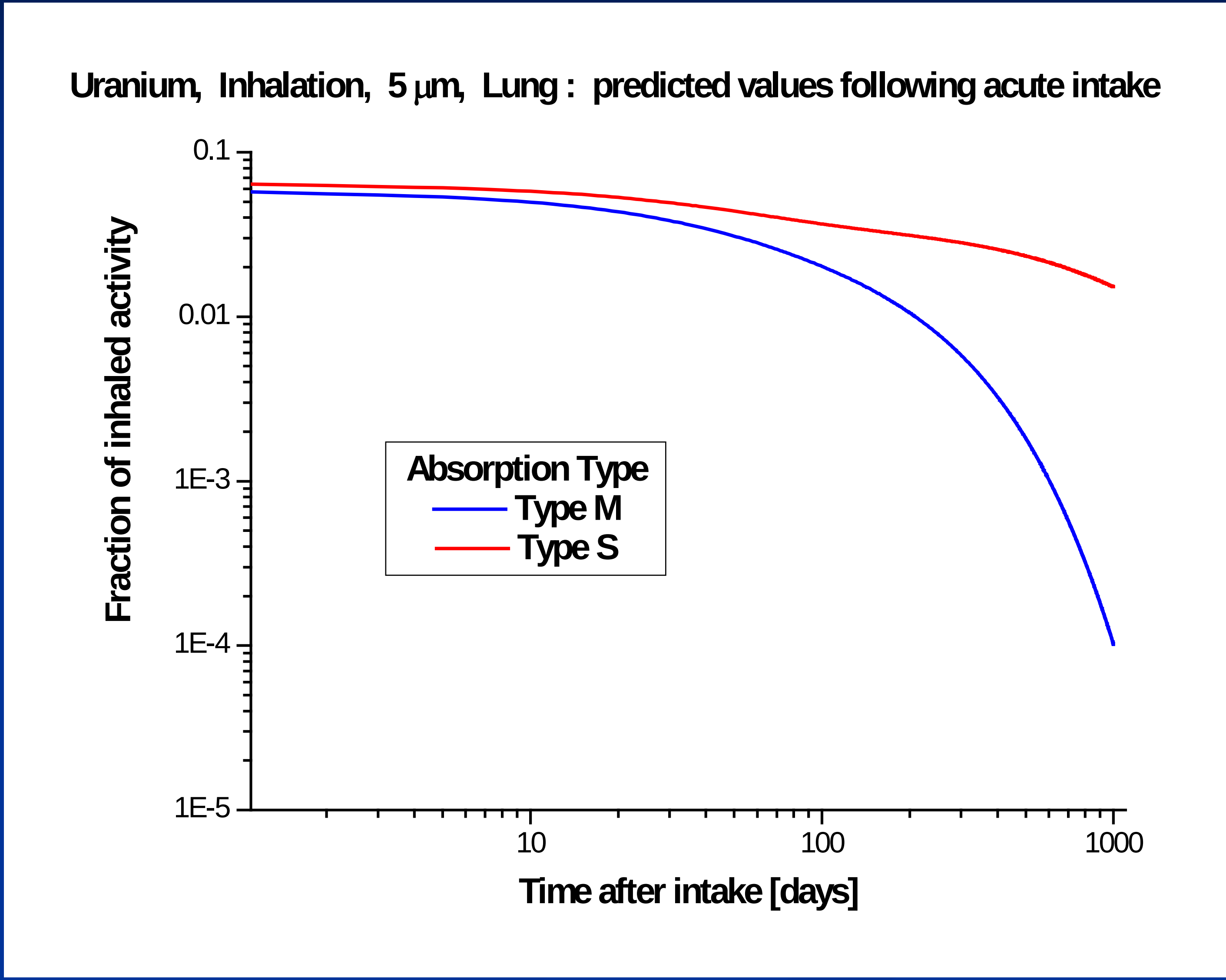
$$I_C = \frac{M(t)}{F_C(t)} \times D$$



예탁유효선량 [Sv] = 섭취량 [Bq] × e_{50} [Sv/Bq]

* ICRP-68(1994)

Intake Retention Fraction due to Absorption type



* ICRP-78(1997)

Effective Dose Coefficients [Sv/Bq]

Nuclide	$t_{1/2}$	Inhalation, $e_{inh}(50)$				Ingestion, $e_{ing}(50)$	
		Type	f_1	1 μ AMAD	5 μ AMAD	f_1	
^{232}U	72.0 y	F	0.020	4.0×10^{-6}[a]	4.7×10^{-6}	0.020	3.3×10^{-7}
		M	0.020	7.2×10^{-6}	4.8×10^{-6}	0.002	3.7×10^{-8}
		S	0.002	3.5×10^{-5}	2.6×10^{-5}	-	-
^{233}U	1.58(05) y	F	0.020	5.7×10^{-7}	6.6×10^{-7}	0.020	5.0×10^{-8}
		M	0.020	3.2×10^{-6}	2.2×10^{-6}	0.002	8.5×10^{-9}
		S	0.002	8.7×10^{-6}	6.9×10^{-6}	-	-
^{234}U	2.44(05) y	F	0.020	5.5×10^{-7}	6.4×10^{-7}	0.020	4.9×10^{-8}
		M	0.020	3.1×10^{-6}	2.1×10^{-6}	0.002	8.3×10^{-9}
		S	0.002	8.5×10^{-6}	6.8×10^{-6}	-	-
^{235}U	7.04(08) y	F	0.020	5.1×10^{-7}	6.0×10^{-7}	0.020	4.6×10^{-8}
		M	0.020	7.2×10^{-6}	4.8×10^{-6}	0.002	8.3×10^{-9}
		S	0.002	7.7×10^{-6}	6.1×10^{-6}	-	-
^{236}U	2.34(07) y	F	0.020	5.2×10^{-7}	6.1×10^{-7}	0.020	4.6×10^{-8}
		M	0.020	2.9×10^{-6}	1.9×10^{-6}	0.002	7.9×10^{-9}
		S	0.002	7.9×10^{-6}	6.3×10^{-6}	-	-
^{238}U	4.47(09) y	F	0.020	4.7×10^{-7}	5.8×10^{-7}	0.020	4.4×10^{-8}
		M	0.020	2.6×10^{-6}	1.6×10^{-6}	0.002	7.6×10^{-9}
		S	0.002	7.3×10^{-6}	5.7×10^{-6}	-	-

* ICRP-68(1994)

IV. 폐내 우라늄 측정 및 선량평가

폐 방사능 측정 장비

- KAERI 폐 방사능 계수기 (BEGe 6530)

* KAERI (2014)

폐 방사능 측정 장비

- KAERI 폐 방사능 분석장비 (MCA)

* KAERI (2014)

폐 방사능 측정 장비

- LLNL 팬톰의 폐 세트 및 교정용 면선원

* KAERI (2014)

폐 방사능 측정 장비

- 교정용 면선원 정보

1991/4/3	Energy(keV)	Yield(%)	GPS
Am-241 (4.21E+04 Bq)	13.90	13.2	5558.5
	17.70	19.5	8211.5
	20.90	4.8	2021.3
	26.40	2.4	1010.6
	59.50	36.0	15159.6
Eu-152 (1.39E+04 Bq)	121.78	28.4	3936.2
	244.69	7.5	1038.1
	344.27	26.5	3672.9
	778.89	12.7	1765.8

* KAERI (2014)

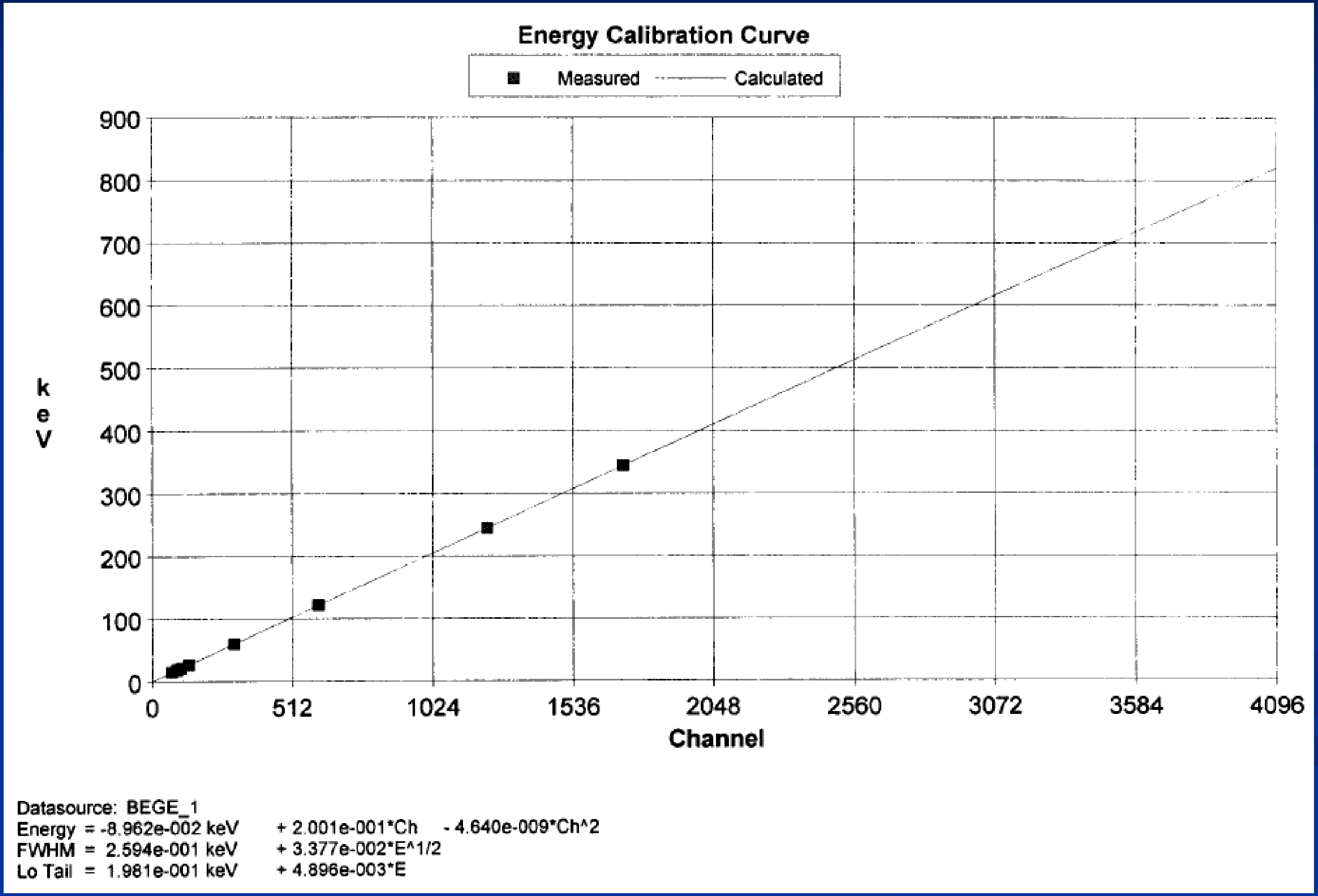
폐 방사능 측정 장비

- LLNL 팬톰 몸통 판 및 덮개
- 가슴벽 지방질량분율 및 두께

Configuration	Adipose Mass Fraction (%)	Chest Wall Thickness (cm)
Torso Plate	0	1.77
Torso Plate + B1	12.8	2.40
Torso Plate + B2	20.4	3.05
Torso Plate + B3	24.3	3.53
Torso Plate + B4	27.4	4.05

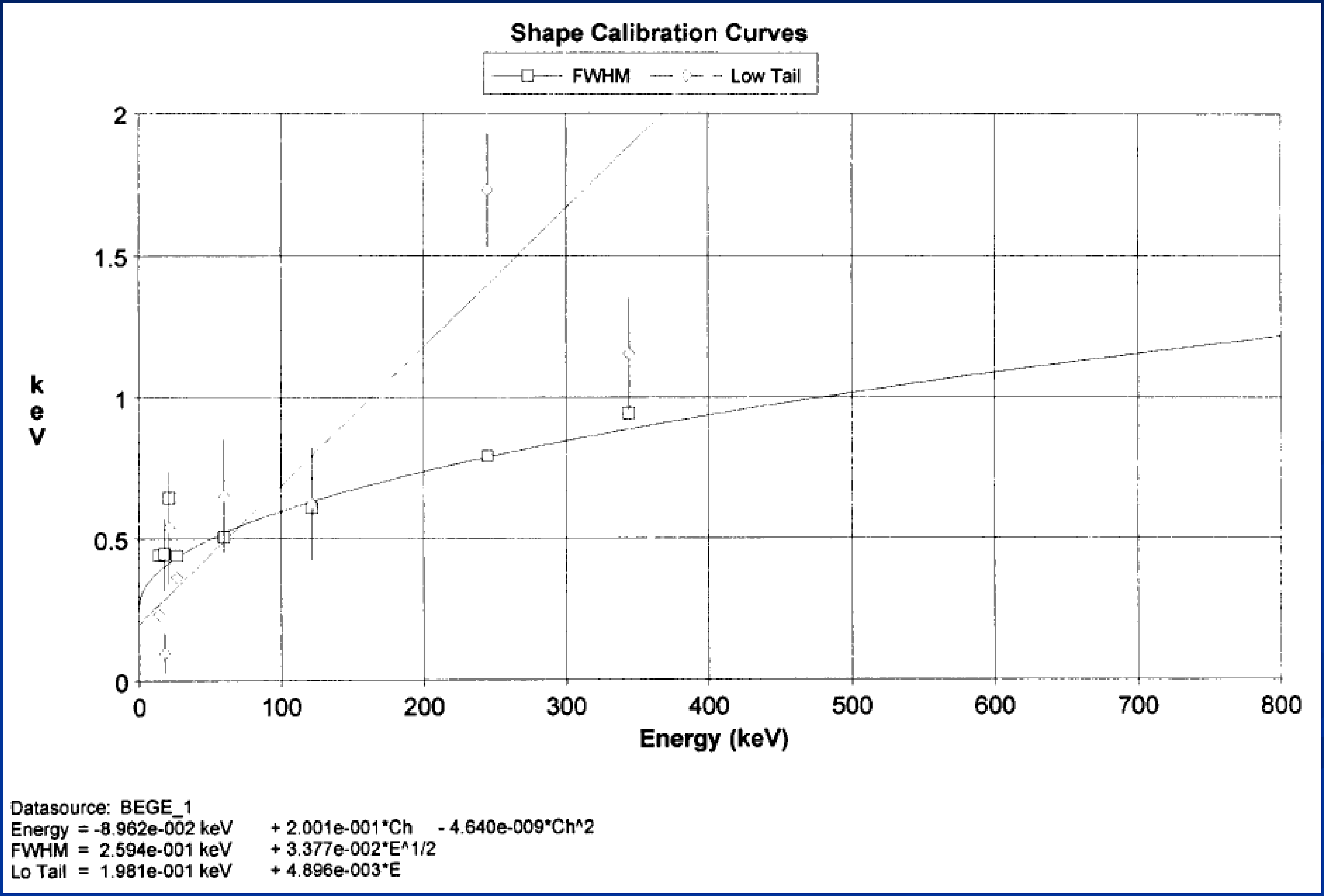
* KAERI (2014)

채널 / 에너지 교정



* KAERI (2014)

채널 / 에너지 교정



* KAERI (2014)

에너지 / FWHM 교정

DET 01

Energy (keV)	Centroid Channel	Centroid error
13.9	70.18	0.01
17.7	89.47	0.33
20.9	104.84	0.22
26.4	132.26	0.00
59.5	297.93	0.00
121.8	608.56	0.02
244.7	1222.21	0.02
344.0	1719.69	0.02

DET 02

Energy (keV)	Centroid Channel	Centroid error
13.9	70.08	0.02
17.7	89.27	0.20
20.9	104.74	0.22
26.4	132.10	0.00
59.5	297.74	0.00
121.8	608.41	0.02
244.7	1222.27	0.01
344.0	1719.80	0.01

SUM

Energy (keV)	Centroid Channel	Centroid error
13.9	70.21	0.02
17.7	89.48	0.24
20.9	105.33	0.22
26.4	132.27	0.00
59.5	297.96	0.01
121.8	608.65	0.01
244.7	1222.37	0.01
344.0	1719.79	0.01

DET 01

Energy (keV)	FWHM Chnnels	FWHM error	FWHM (keV)
13.9	2.20	0.03	0.39
17.7	2.22	0.64	0.40
20.9	3.23	0.46	0.41
26.4	2.20	0.01	0.43
59.5	2.52	0.01	0.52
121.8	3.04	0.03	0.63
244.7	3.96	0.03	0.79
344.0	4.71	0.03	0.89

* FWHM(keV) = 0.259 + 0.034*E^1/2

DET 02

Energy (keV)	FWHM Chnnels	FWHM error	FWHM (keV)
13.9	2.10	0.04	0.35
17.7	2.17	0.39	0.37
20.9	3.19	0.40	0.38
26.4	2.10	0.01	0.40
59.5	2.42	0.01	0.49
121.8	2.95	0.03	0.60
244.7	3.83	0.03	0.76
344.0	4.41	0.02	0.85

* FWHM(keV) = 0.241 + 0.034*E^1/2

SUM

Energy (keV)	FWHM Chnnels	FWHM error	FWHM (keV)
13.9	2.24	0.04	0.39
17.7	2.36	0.45	0.40
20.9	4.52	0.44	0.42
26.4	2.23	0.01	0.44
59.5	2.54	0.01	0.53
121.8	3.06	0.04	0.64
244.7	3.93	0.02	0.80
344.0	4.64	0.02	0.91

* FWHM(keV) = 0.256 + 0.035*E^1/2

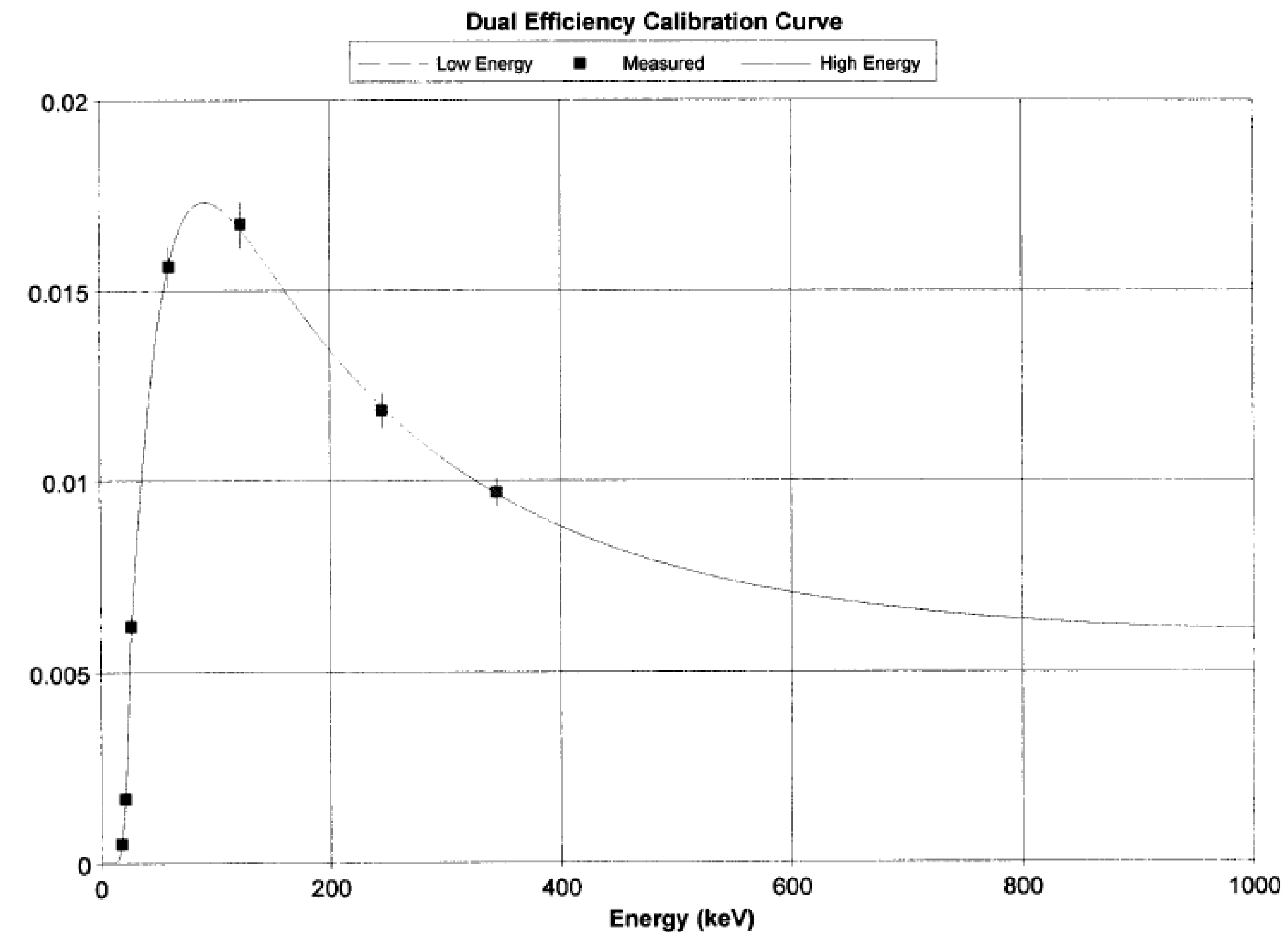
* KAERI (2014)

검출효율 교정 (CWT=1.77 cm, 에너지별)

CWT 1.77	under 26.4 :2차식		over 26.4 :3차식	
energy (keV)	Calcu Eff	Measu Eff	Measu err(%)	Dev.(%)
17.7	5.00E-04	5.00E-04	3.59	0.00
20.9	1.67E-03	1.67E-03	3.55	0.00
26.4	6.18E-03	6.19E-03	3.53	-0.08
59.5	1.57E-02	1.56E-02	3.50	0.38
121.8	1.66E-02	1.67E-02	3.81	-0.81
244.7	1.19E-02	1.18E-02	3.84	0.89
344.0	9.65E-03	9.69E-03	3.81	-0.41

* KAERI (2014)

검출효율 교정 (CWT=1.77 cm, 에너지별)



Datasource: C:\ABACOS2K\CTRS\CTR01\ARR01\EF030045.NEW
ln(Eff) = -6.566e+001 + 3.241e+001*ln(E) - 4.247e+000*ln(E)^2
ln(Eff) = -2.702e+001 + 1.300e+001*ln(E) - 2.375e+000*ln(E)^2 + 1.379e-001*ln(E)^3

* KAERI (2014)

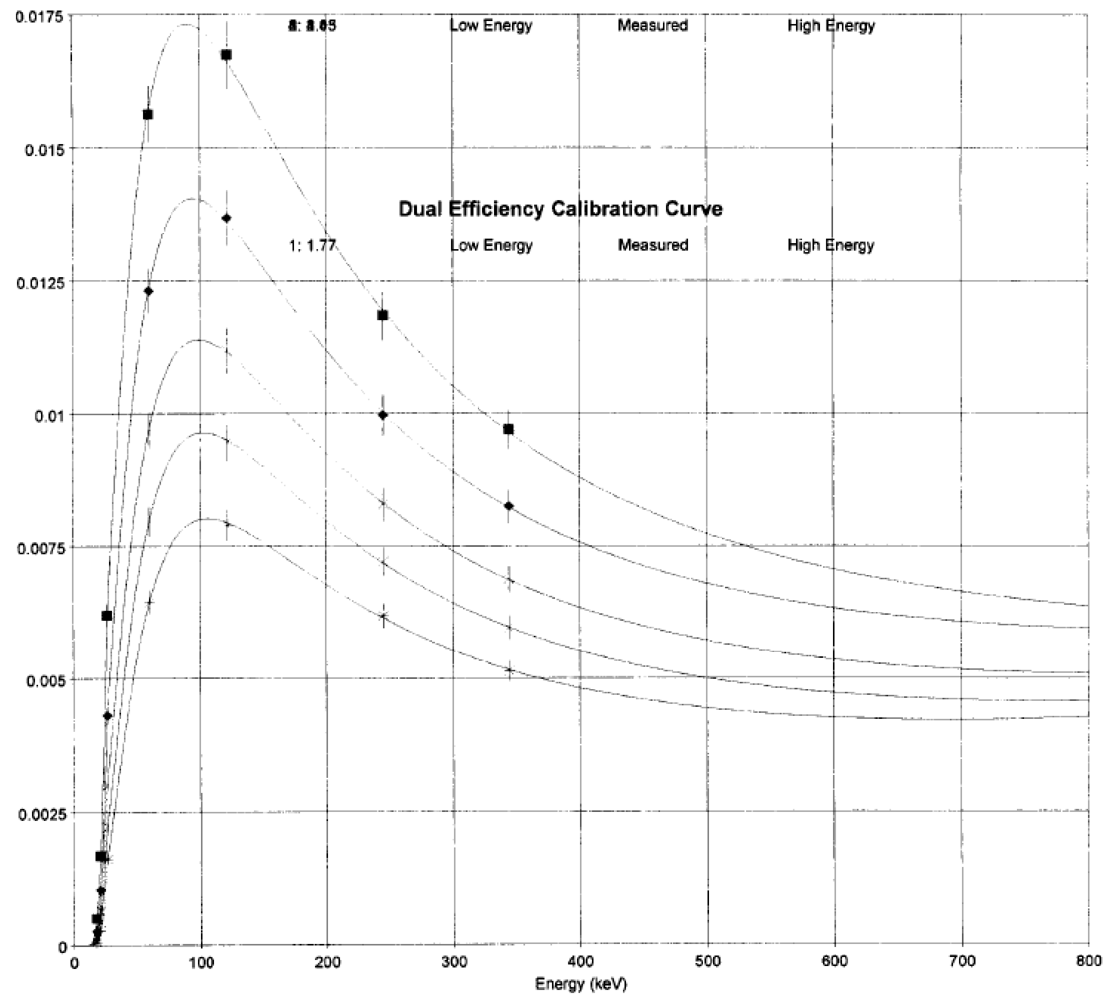
검출효율 교정 (CWT별, 에너지별)

$$CWT = 60\frac{W}{H} - 1$$

CWT : 가슴벽두께 (mm)

W : 몸무게 (kg)

H : 키 (cm)



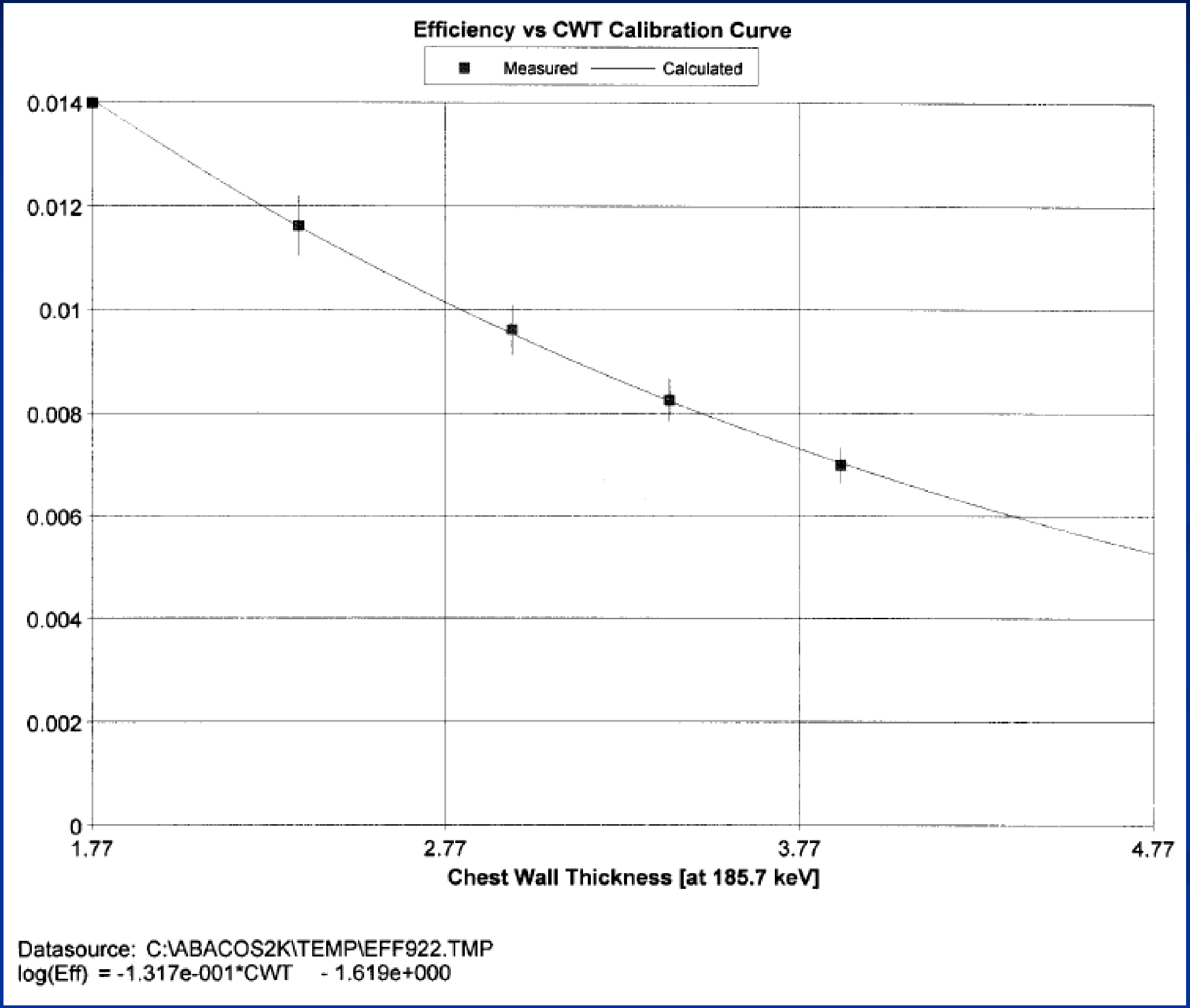
Datasource: C:\ABACOS2K\CTRS\CTR01\ARR01\EF030050.NEW

ln(Eff) = -6.566e+001 + 3.241e+001*ln(E) - 4.247e+000*ln(E)^2

ln(Eff) = -2.702e+001 + 1.300e+001*ln(E) - 2.375e+000*ln(E)^2 + 1.379e-001*ln(E)^3

* KAERI (2014)

검출효율 교정 (185.7 keV, CWT별)



* KAERI (2014)

교정 검증

Nuclide	Energy(keV)	Acivity(Bq)	cwt 1.77 cm		cwt 2.40 cm		cwt 3.05 cm		cwt 3.53 cm		cwt 4.05 cm				
			측정값	상대편중	측정값	상대편중	측정값	상대편중	측정값	상대편중	측정값	상대편중	평균상대편중(B_r)	상대정밀도 ∣S_B∣	RMSE
U-238	63	5,956	4,981	-0.1637	5,066	-0.1495	5,132	-0.1384	5,060	-0.1505	3,959	-0.3353	-0.1875	0.0831	0.2051
U-235	185	277	278	0.0035	272	-0.0169	275	-0.0082	269	-0.0291	268	-0.0329	-0.0167	0.0150	0.0224

* 각 측정회수에서의 두께는 가슴벽 두께(cm)를 의미한다.
* 각 가슴벽두께에서의 측정값은 5번 측정값의 평균값이며, 각 5번 측정 시 B_r, ∣S_B∣ 및 RMSE 는 별도의 첨부자료(엑셀파일)에 있음

* 교정차수 : Low : 2차
  High : 3차
* 측정시간 : 1800sec

* 허용범위 : $-0.25 \leq$ 평균상대편중(B_r) ≤ 0.5
  상대정밀도 ∣S_B∣ ≤ 0.4
  RMSE ($\sqrt{B_r^2+S_B^2}$) ≤ 0.25

평균상대편중

$$B_r = \overline{B_{ri}} = \frac{\sum_{i=1}^{n} B_{ri}}{n}$$

$$B_{ri} = \frac{A_i - A_{ai}}{A_{ai}}$$

상대정밀도

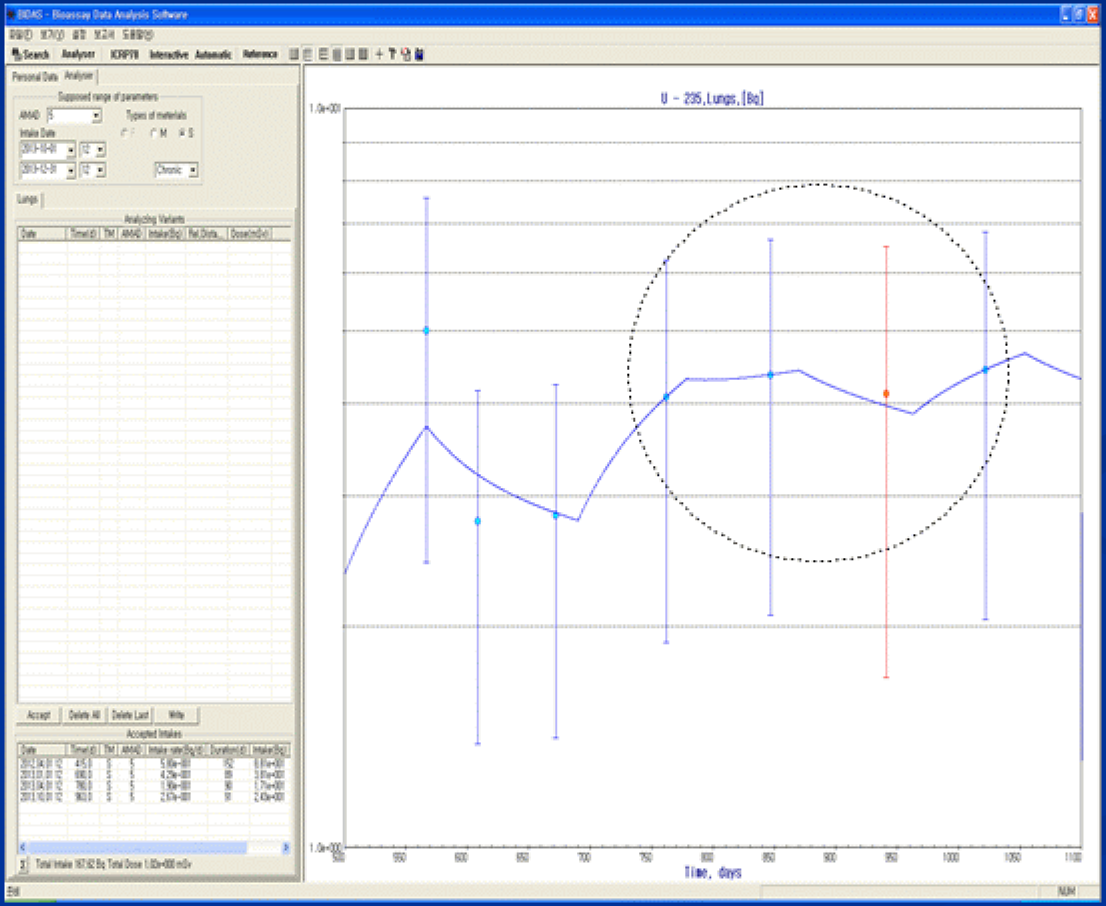
$$S_{Br} = \sqrt{\frac{\sum_{i=1}^{n}\left(B_{ri} - B_r\right)^2}{n-1}}$$

Root Mean Squared Error

$$\mathrm{RMSE} = \sqrt{B_r^2 + S_B^2} \leq 0.25$$

체내 오염자 측정 결과

- U-235 측정결과 및 연속섭취율 평가 (예 3)



- 폐 우라늄 방사능
  - 03/14, 4.07 Bq
  - 06/07, 4.36 Bq
  - 09/09, 4.11 Bq
  - 11/29, 4.43 Bq

- 연속섭취율
  - 1, 2, 4분기 각각 섭취
  - 1분기 : 0.429 Bq/d
  - 2분기 : 0.191 Bq/d
  - 3분기 : 0 Bq/d
  - 4분기 : 0.267 Bq/d

체내 오염자 내부선량평가

- 우라늄 섭취량 평가

^{235}U 섭취량(Bq) = ^{235}U 연속섭취율(Bq/d) x 섭취기간(d)

^{234}U 섭취량(Bq) = ^{235}U 섭취량(Bq) x (f_{234} / f_{235})

^{238}U 섭취량(Bq) = ^{235}U 섭취량(Bq) x (f_{238} / f_{235})

- ^{235}U 질량%별 U 전방사능에 대한 ^{234}U, ^{235}U, ^{238}U 방사능분율

^{235}U 질량%	f_{234}	f_{235}	f_{238}
0.2	0.1848	0.0102	0.8050
0.72	0.4680	0.0234	0.5085
3.5	0.8094	0.0357	0.1549
4.5	0.8421	0.0364	0.1216
20.0	0.9412	0.0361	0.0227
93.0	0.9669	0.0328	0.0003

* KAERI (2014)

체내 오염자 내부선량평가

- 우라늄 예탁유효선량 평가

$$H_{50,\,E} = I_{234} \times e_{inh}(50)_{234} + I_{235} \times e_{inh}(50)_{235} + I_{238} \times e_{inh}(50)_{238}$$

- $H_{50,E}$: 우라늄 흡입섭취에 따른 예탁유효선량 (Sv)
- I_{234}, I_{235}, I_{235} : ^{234}U, ^{235}U, ^{235}U 섭취량(Bq)
- $e_{inh}(50)_{234,\,235,\,238}$: $^{234,\,235,\,238}U$ 의 예탁유효선량 환산계수(Sv/Bq)

* KAERI (2014)

Thank you !

KAERI Lung Counting System